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19. ABSTRACT.

Detailed discussions of progress during the first two years of this grant can be found in "Progress and Forecast Reports" of the same title published on 1 May of 1987 and 1 May of 1988. Brief descriptions of published papers, in-house reports, or abstracts sponsored in whole, or in part, by this grant are presented here, along with detailed discussions of progress during the final year of the grant. A sampling of highlights from these investigations follows. — includes: 1) —

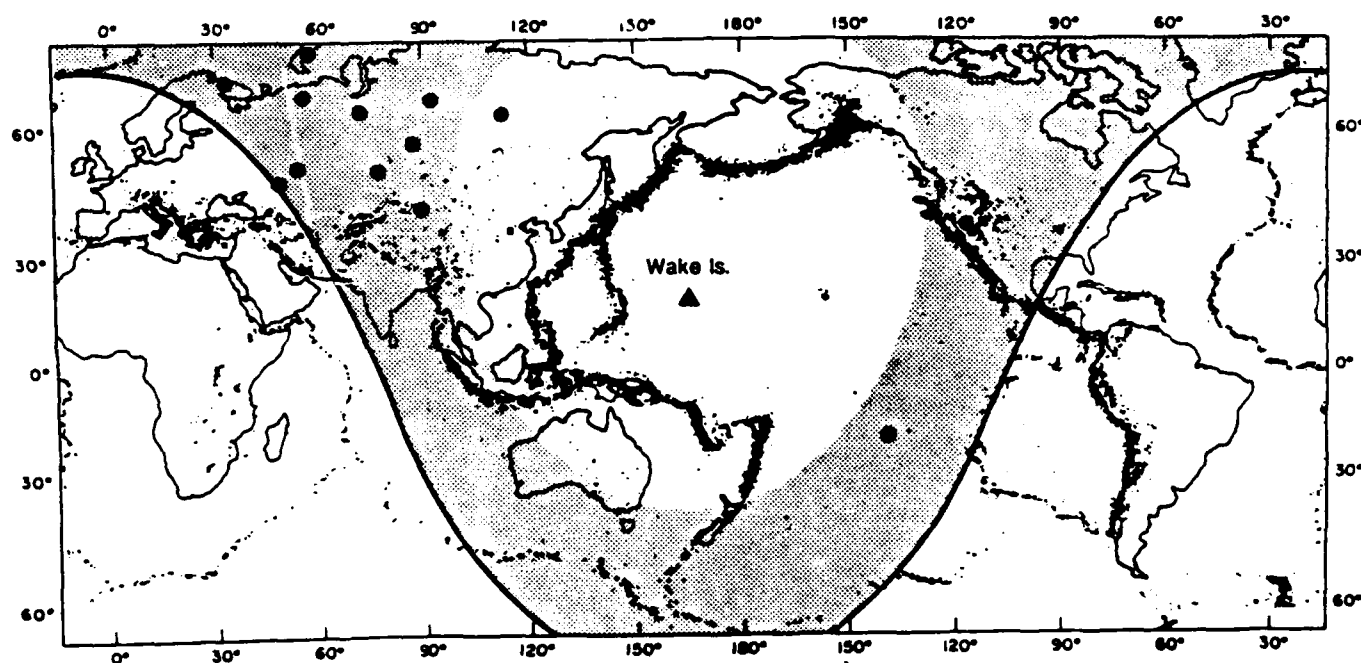
- There is a strong correlation between ocean surface wind velocities and ocean bottom noise in the frequency range of 0.5 to 30 Hz; 2)
- Sites favorable for the detection of weak short-period signals may be found on the deep ocean bottom in regions with low wind; 3)
- The yield of large explosions might be disguised by siting the explosion at a location that selectively defocuses energy towards continents where most seismic stations are located; 4)
- The Wake Island array provides very stable measures of yield; 5)
- A moderate underground nuclear explosion appropriately placed in a subduction zone (e.g., the Kuril-Kamchatka portion of the circum-Pacific arc) could escape detection by the existing conventional network of continental and island seismic stations; 6)
- A new trench extending over 5000 km from the Marianas trench to the Tonga trench may be forming in the southwest Pacific; 7)
- A significant number of earthquakes, unreported by the conventional worldwide network of seismic stations, are located within the interior of the Northwestern Pacific Basin. *Seismicity; Ocean basins. (EDC)*
- In an analysis of data from a 1500-km-long linear ocean bottom hydrophone array (including the Wake array), the apparent Q for Po is found to increase with frequency from about 300 at 2.5 Hz to 1500 at 17.5 Hz, while the apparent Q for So phases increases from about 400 at 2.5 Hz to 3000 at 22.5 Hz.
- For the same experiment cited above, Po and So travel time lines are found to be:

$$T = X/7.96 \pm 0.05 \text{ km/sec} - 7.21 \pm 2.40 \text{ sec for Po, and}$$

$$T = X/4.58 \pm 0.06 \text{ km/sec} - 12.84 \pm 7.61 \text{ sec for So.}$$
- A substantial number of significant earthquakes in the Marianas subduction zone has escaped detection by the existing conventional network of continental and island seismic stations.
- The deep interiors of ocean basins may be more seismically active than is generally believed. Unusual distributions of epicenters may be indicative of: (1) isostatic readjustments; (2) stress and deformations consistent with plate motions, and/or (3) nascent subduction zones, ridge systems, or hot spots.
- In some regions, the seismicity associated with subduction zones extends several hundred kilometers out into the ocean beyond what are now considered to be the leading edges of subduction.
- More accurate assessments of ocean seismicity could provide explanations for unresolved perturbations in the earth's gravity field.

HYDROPHONE INVESTIGATIONS OF EARTHQUAKES AND EXPLOSION GENERATED HIGH-FREQUENCY SEISMIC PHASES

AFOSR-TR- 89-1206



Final Technical Report
to the
Air Force Office of Scientific Research
30 June 1989

Final Technical Report

to the

Air Force Office of Scientific Research

from

Daniel A. Walker

Hawaii Institute of Geophysics

University of Hawaii

Honolulu, Hawaii 96822

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Title of Work: Hydrophone Investigations of Earthquakes and Explosion

Generated High-Frequency Seismic Phases

[illegible]

FACT SHEET¹

Wake Array

- Provides exclusive continuous coverage of the Western Pacific Basin - an area as large as the entire North American Continent. Its borders include the earth's most seismically active subducting margins, with the Kuril-Kamchatka region an area of special interest.
- Is one of the world's largest arrays, containing ocean-bottom and SOFAR hydrophones; and, to our knowledge, is the world's only continuously recording deep-ocean array. The bottom sub-array consists of six elements at 24-km spacings with a maximum aperture of 42 km. Including SOFAR hydrophones at other locations, the maximum aperture of the array is 318 km.
- Is uniquely located relative to the world's major underground test sites - nearly all are located in the highly efficient propagational distance range of about 60- to 90-degrees. The three most frequently used and geologically diverse being at nearly identical epicentral distances. Δ 's for E. Kazakh, Nevada, and the Tuamotu's are 73.0, 68.1, and 67.9 degrees, respectively. [Distances from 30° to 90° are generally regarded as the best for comparative studies of P phases from explosions; e.g., see "Differences in Upper Mantle Attenuation between the Nevada and Shagan River Test Sites: Can the Effects be Seen in P-Wave Seismograms?" by A. Douglas, Bull. Seism. Soc. Am., 77, 270-276, 1987.]
- Is found to have extremely low noise levels at frequencies higher than 3 Hz, a fact which is given added significance by the general belief that lower magnitude explosions are relatively richer in higher frequencies and by the observation at Wake of frequencies as high as 7 Hz in the P phases from large underground nuclear explosions. Po, So, and T-phases also have their dominant values at frequencies in excess of 3 Hz.
- Is uniquely located relative to the epicenters of unreported earthquakes in the interior of the Northwestern Pacific Basin and along the recently postulated Micronesian trench. Earthquakes unreported by conventional worldwide seismic stations have been located throughout the interior of the basin using data from this array.
- Is capable of recording 16 channels of digital data with a dynamic range of 96dB and absolute timing to within one millisecond. Other features include power failure recoverability, 80 samples per second per channel, and common type format.
- Has successfully operated for 72 months with no major malfunctions.

¹Evidence for statements given may be found in "Hydrophone Investigations of Earthquake and Explosion Generated High-Frequency Seismic Phases", Technical Report, AFOSR, 31 December 1984 and in an AFOSR report of the same title dated 30 April 1986.

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III. "Seismicity of the Interiors of Plates in the Pacific Basin", by D. Walker.	
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ABSTRACT

Detailed discussions of progress during the first two years of this grant can be found in "Progress and Forecast Reports" of the same title published on 1 May of 1987 and 1 May of 1988. Brief descriptions of published papers, in-house reports, or abstracts sponsored in whole, or in part, by this grant are presented here, along with detailed discussions of progress during the final year of the grant. A sampling of highlights from these investigations follows.

- There is a strong correlation between ocean surface wind velocities and ocean bottom noise in the frequency range of 0.5 to 30 Hz.
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- The Wake Island array provides very stable measures of yield.
- A moderate underground nuclear explosion appropriately placed in a subduction zone (e.g., the Kuril-Kamchatka portion of the circum-Pacific arc) could escape detection by the existing conventional network of continental and island seismic stations.
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- A significant number of earthquakes, unreported by the conventional world-wide network of seismic stations, are located within the interior of the North-western Pacific Basin.
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- In some regions, the seismicity associated with subduction zones extends several hundred kilometers out into the ocean beyond what are now considered to be the leading edges of subduction.
- More accurate assessments of ocean seismicity could provide explanations for unresolved perturbations in the earth's gravity field.

**CUMULATIVE SUMMARY OF RESEARCH ACCOMPLISHED
THROUGH THE TOTAL OF PARTIAL SUPPORT OF AFOSR (I.E.,
INCLUDING GRANTS OR CONTRACTS PRIOR TO 86-0039)**

PUBLICATIONS

- 1980 Walker, D.A., Hydrophone recordings of underground nuclear explosions, *Geophys. Res. Lett.*, **7**, 465-467.

Possibly the first reported use of hydrophones for recording underground nuclear explosions.

- 1983 McCreery, C.S., Walker, D.A., and Sutton, G.H., Spectra of nuclear explosions, earthquakes, and noise from Wake Island bottom hydrophones, *Geophys. Res. Lett.*, **10**, 59-62.

More quantitative analysis examining the thresholds of detection and enhancements with array processing.

- 1984 Walker, D.A., Deep ocean seismology, *Eos*, **65**, 2-3.

A discussion of the advantages of recording earthquakes and explosions on the ocean floor.

- 1985 Walker, D.A., McCreery, C.S., and Oliveira, F.J., Kaitoku Seamount and the mystery cloud of 9 April 1984, *Science*, **227**, 607-611.

Data from the Wake array was used to investigate possible causes - one suggestion being a nuclear explosion.

- 1985 McCreery, C.S., and Walker, D.A., Spectral comparisons between explosion P signals from the Tuamotu Islands, Nevada, and eastern Kazakh, *Geophys. Res. Lett.*, **12**, 353-356.

Because Wake is nearly equidistant from these three geologically diverse sites and at the highly efficient propagation distance of about 70 °, comparisons of spectra

added support to existing theories and observations.

- 1985 Walker, D.A., and McCreery, C.S., Significant unreported earthquakes in "aseismic" regions of the Western Pacific, *Geophys. Res. Lett.*, **12**, 433-436.

A major concern for the future, notwithstanding "glasnost", is that significant underground explosions in subduction zones and in the interiors of ocean plates could escape detection by the conventional network of continental and island stations. This study brought such a possibility to our attention and led to many subsequent investigations of ocean seismicity and the guided ocean phases Po and So.

- 1986 Kroenke, L.W., and Walker, D.A., Evidence for the formation of a new trench in the Western Pacific, *Eos*, **67**, 145-146.

Seismicity associated with a postulated subduction zone escaped detection by the conventional worldwide network of stations, a theme of potential importance to the nuclear detection community.

- 1987 Butler, R., McCreery, C.S., Frazer, L.N., and Walker, D.A., High-frequency seismic attenuation of oceanic P- and S-waves in the Western Pacific, *J. Geophys. Res.*, **92-B2**, 1383-1396.

A quantification of the spectral content and variations of Po/So phases. Such phases recorded by ocean bottom instrumentation are the principal phases used in the detection of otherwise unreported earthquakes along ocean plate margins or in ocean plate interiors.

- 1987 Walker, D.A., and McCreery, C.S., Po/So phases: propagation velocity across a 1,500-km-long, deep ocean hydrophone array, *J. Phys. Earth*, **35**, 111-126.

Quantification of the velocities associated with Po/So phases.

- 1987 McCreery, C.S., Yield estimation from spectral amplitudes of direct P and P coda recorded by the Wake Island deep ocean hydrophone array, *Bull. Seism. Soc. Am.*, **77**, 1748-1766.

An analysis of the stability of yield estimates possible with data from the Wake array and observed focusing and defocusing effects at the Western Kazakh test site.

- 1988 Walker, D., Significant unreported earthquakes in the Marianas subduction zone, *J. Phys. Earth*, **36**, 43-52.

Additional evidence of events located along a plate margin with data from the Wake array, but unreported by the conventional network of seismic stations.

- 1988 Walker, D., and McCreery, C., Deep ocean seismology: seismicity of the North-western Pacific basin interior, *Eos*, **69**, 737, 742-743.

Additional evidence of events located within an ocean plate interior with data from the Wake array, but unreported by the conventional network of seismic stations.

- 1988 McCreery, C., and Duennebie, F., Ambient deep ocean noise characteristics, 0.5 to 30 Hz, from the Wake Island array and the ocean sub-bottom seismometer, "Proceedings of a Workshop on ULF/VLF (0.001 to 50 Hz) Seismo-Acoustic Noise in the Ocean," G.Sutton, Editor, A15-A23.

For high frequencies (≥ 3 Hz), we maintain that the earth's quietest sites may be found in deep ocean basins where average surface wind velocities are low. Nuclear explosions are rich in high frequencies and this richness increases in a relative sense with explosions having lower yields. Therefore, studies of ocean noise are important.

- 1988 Duennebie, F., and McCreery, C., Downhole and seafloor seismic measurements made by the Hawaii Institute of Geophysics: past, present, and future, 232-258, in "Proceedings of a Workshop on Broad-Band Downhole Seismometers in the Deep Ocean," JOI, 331 p.

A general review and discussions of observations made by HIG.

- 1988 Nagumo, S., and Walker, D., Trans-oceanic telecommunications cables: re-use for ocean bottom geoscience observatories , 268-276, in "Proceedings of a Workshop on Broad-Band Downhole Seismometers in the Deep Ocean," JOI, 331 p.

Presentation of the concept to use transoceanic coaxial cables now being replaced by fiber optic cables as geoscience observatories. Nuclear explosions could be recorded throughout the world's oceans (in the Atlantic, Pacific, and Indian oceans) in international waters.

- 1989 Nagumo, S., and Walker, D., Ocean bottom geoscience observatory: reuse of trans-oceanic telecommunications cables, *Eos*, **70-26**, 673, 677.

A popularized version of the preceeding report for distribution to the worldwide community of ocean scientists.

- 1989 Walker, D. (compiler), Seismicity of the interiors of plates in the Pacific Basin, a map in Mercator projection, School of Ocean and Earth Science and Technology, University of Hawaii, 2525 Correa Rd., Honolulu, Hi. 96822.

A map showing that the interiors of plates in the Pacific Basin are more seismically active than is generally believed. Unusual patterns of seismicity could be related to isostatic readjustments, stresses and deformations due to plate motions, or nascent hot spots, ridge systems, or subduction zones.

OTHER REPORTS

During this same time period, 19 abstracts have been published, mostly on topics already given in the publications listing. One notable exception is the following.

- 1988 McCreery, C., and Walker, D., The Wake Island hydrophone array, *Seism. Res. Lett.*, **59-1**, 22.

Presented T-phase recordings from small Tuamotu nuclear explosions well recorded by the Wake array at distances in excess of 10,000 km.

Also, annual technical reports to AFOSR have been widely distributed, and these have discussed many of the topics presented here in much greater detail. A supplementary report worth special mention follows.

- 1986 Walker, D., McCreery, C., and Oliveira, F., Wake island hydrophone array: recordings of worldwide underground nuclear explosions from September 1982 through December 1984, Data Report for AFOSR and ACDA, 201 p., April 1986.

In this report spectral analyses and comparisons were made for underground nuclear explosions recorded by the Wake array from ten of the thirteen test sites used by various nations from September 1982 through December 1984. Distances ranged from 55° to 80° , with four sites at nearly identical distances of about 68° . The Eastern Kazakh explosions were richest at the widest range of frequencies. Siberian and Central Siberian signals were peculiar for their strength at high frequencies relative to their weakness at low frequencies. Signals from remaining sites were confined to frequencies from 1 to 2.5 Hz. The poorest recordings, in terms of signal strengths relative to mb values, were from the Tuamotus and Nevada.

DISCUSSION

Originally the major objectives of our research for AFOSR were to: (1) evaluate the possible advantages of recording underground nuclear explosions on the ocean floor and (2) compare signals from differing test sites. These tasks related to such traditional issues as detection thresholds, discrimination, yield estimates, and selective defocusing of seismic energy. We have succeeded in addressing all of these issues in publications appearing in peer-reviewed journals. Some definitive conclusions were reached and some preliminary conclusions or suggestions still require additional data. Much of the required

and anticipated data did not materialize because of Russia's self-imposed moratorium on testing.

In addition to achievements related to our original objectives, several topics of basic importance to the earth sciences were extensively examined with data from the Wake array. These included studies of: (a) ocean noise levels and their relation to ocean surface wind velocities; (b) otherwise unreported earthquakes in the interior of the Northwestern Pacific Basin, and (c) submarine volcanic eruptions in the Marianas. These studies led, in turn, to: (a) the postulation of a new subduction zone forming in the southwest Pacific (the Micronesian Subduction Zone), (b) the publication of a seismicity map for the interiors of the Pacific Basin which shows unusual patterns and clusters of seismicity, as well as earthquakes extending several hundred kilometers out into the oceans beyond what is considered to be the leading edges of subduction; and (c) a demonstration of the hydrophones utility in detecting and discriminating otherwise undetected submarine acoustic signals.

As a result, new initiatives (i.e., publications in preparation or in review, and proposals supported, in review, or in preparation) have been undertaken which will focus on the following topics: (1) ocean noise over a broader range of frequencies; (2) more accurate assessments of the seismicity of ocean plate interiors; (3) the use of hydrophones in monitoring acoustical signals generated along ridge systems; and (4) the reuse of transoceanic telecommunications cables as geoscience observatories.

FINAL REMARKS

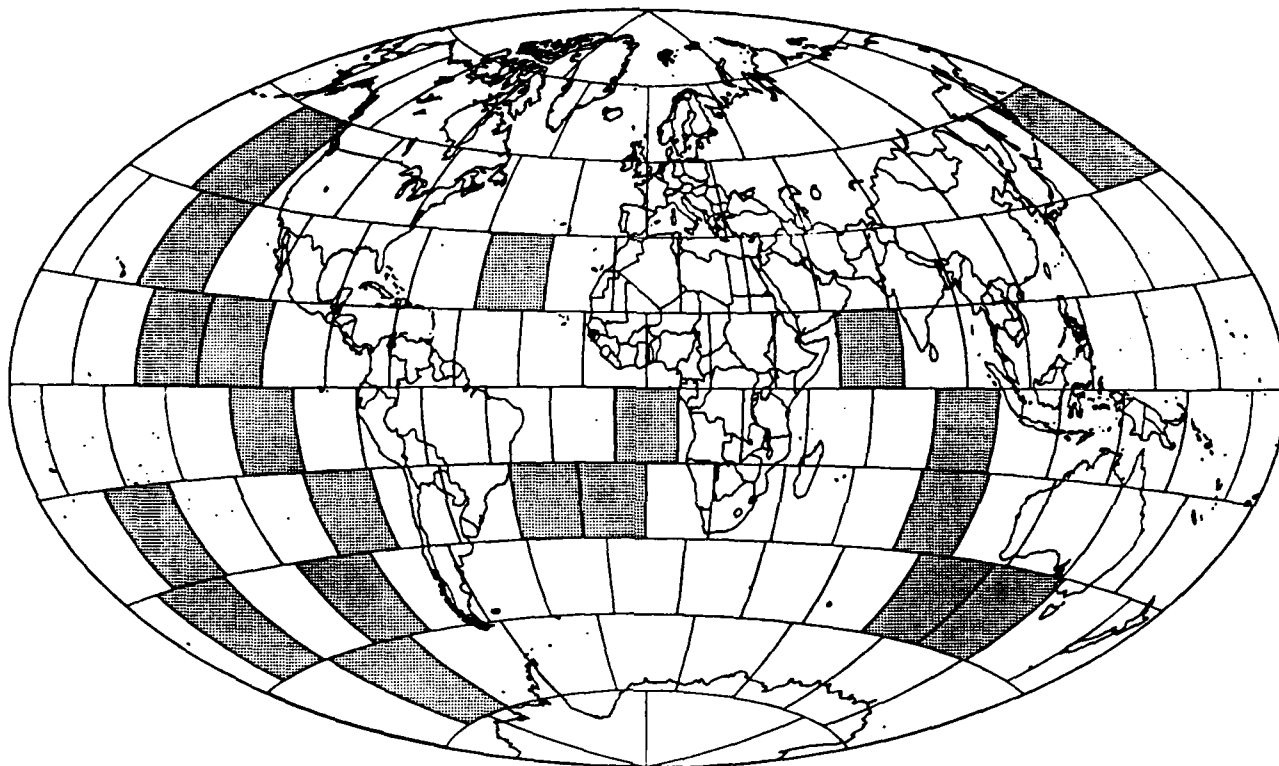
In terms of basic research, we believe that these initiatives are consistent with providing the data necessary for major advancements in earth sciences. Regarding topics of special interest to AFOSR, we believe that: (1) the recording of nuclear explosions on the ocean floor should still be an important concern of the detection and discrimination community (see Appendix II); (2) this discipline is still in its infancy; and (3), all

of the initiatives mentioned are of fundamental importance to the recording of nuclear explosions on the ocean floor.

Regarding studies of the seismicity of ocean interiors, we believe that previously unknown patterns of seismicity in ocean interiors could have important implications for a comprehensive understanding of the earth's gravitational field.

Proceedings of a Workshop on Broad-Band Downhole Seismometers in the Deep Ocean

Woods Hole Oceanographic Institution
Woods Hole, Massachusetts, 02543, USA



April 26-28, 1988

Convenors: G.M. Purdy and Adam M. Dziewonski

*Sponsored by the Joint Oceanographic
Institutions, Inc. and the U.S. Science Advisory Committee*

DOWNHOLE AND SEAFLOOR SEISMIC MEASUREMENTS MADE BY THE HAWAII INSTITUTE OF GEOPHYSICS: PAST, PRESENT, AND FUTURE

Fred Duennebie and Charles McCreery
Hawaii Institute of Geophysics, 2525 Correa Road
Honolulu, HI 96822

Abstract

Various measurements of seismic signals and ambient noise in the oceanic water column and on or below the ocean bottom have been made by the Hawaii Institute of Geophysics (HIG) over the past two decades. Below the ocean bottom, data have been collected by HIG's Ocean Sub-bottom Seismometer (OSS) from deployments down four Deep Sea Drilling Project (DSDP) drillholes; measurements on the seafloor have been made using HIG Ocean Bottom Seismometers (OBS's) and using the Wake Island Hydrophone Array (WIA); and water-column measurements have been made using WIA hydrophones. These data can answer some questions relevant to the planning of future long-term seismic instrumentation in the oceans. The first question is where to site sensors within the ocean-sediment-basement column in order to maximize the signal-to-noise ratio and the signal fidelity of various seismic and acoustic signals of interest. The data show that for frequencies between about 0.5 and 30 Hz, signal-to-noise can be increased and signal fidelity can be improved by siting the sensors below the ocean-sediment interface. These changes are especially pronounced on horizontal sensors. Although siting the sensors below the ocean bottom is clearly advantageous, it is not clear from the data just how deep into the sediments or basement it is necessary to go in order to achieve a significant improvement in signal-to-noise and signal fidelity. Another important question is where to site future ocean seismometers regionally in order to avoid sources of ambient ocean noise that can reduce signal-to-noise ratios. The long-term data provided by WIA, OSS, and the OBS's show that there are many significant sources of noise between 0.1 and 30 Hz that can be avoided by careful siting. These noise sources include: (1) high surface winds, (2) coastlines, (3) high bottom currents, (4) shipping, (5) hurricanes, typhoons, and cyclones, and (6) whales. In addition, the successes and failures of the electrical and mechanical design of HIG instruments provide useful information for the design of future ocean-environment seismic systems.

INTRODUCTION

Data collected and experience gained by the Hawaii Institute of Geophysics (HIG) over the past 10 years are applicable to the current goal of collecting new broadband long-term seismic data in the oceans to fill the gap in the worldwide data set. Existing HIG data include measurements made by seismometers both on and below the ocean floor, and by ocean bottom hydrophones. The data are generally in the short-period seismic band, ranging from the microseism peak at approximately 0.25 Hz to the upper frequency limit of teleseismic Po, So, and T phases at around 30 Hz. These data provide information about short-period ambient noise levels in different oceanic regions as well as at different depths in the water column and below the sea floor. They also provide information about signal-to-noise ratios as a function of depth below the sea floor for various signal sources. HIG experiences in designing, building, deploying, and recovering ocean bottom and sub-bottom seismic instruments have demonstrated numerous advantages and disadvantages. This information should be applied, when applicable, to future instrumentation and field work. Thus, it is the goal of this report to summarize the HIG ocean seismic work from

both a science and engineering standpoint, especially as it pertains to evolving plans for future seismic data collection in the oceans.

INSTRUMENTATION

Ocean-Bottom Seismometers (OBS's)

The HIG ocean bottom seismometer program began in the early 1970's. By the mid-1970's a design called the Pop-up OBS or POBS had evolved and was being used on a regular basis for refraction and earthquake studies. The POBS consisted of: (1) an explosive-bolt-releasable lead anchor with two (redundant) preset release timers to fire and bolts, (2) a main pressure case containing a vertical and horizontal seismometer, preamplifiers and gain-ranging electronics, a clock, and up to three slow-speed four-channel cassette tape recorders, (3) a hydrophone connected by cable to the main pressure case, (4) recovery floats (glass spheres), (5) two surface-activated recovery strobe lights, and (6) two surface-activated recovery radio transmitters. The instrument was deployed from a ship by dropping it into the water and letting it sink freely to the ocean bottom. It would be recovered at a later pre-determined time, when the release timers would fire the explosive bolts, releasing the lead anchor and causing the package to rise to the surface. The floating package would then be located from the ship by using an onboard radio-direction-finding receiver tuned to the recovery radio transmitters and by scanning the ocean surface for the strobe lights (recovery was generally done at night). The POBS was capable of collecting up to six weeks of data at frequencies up to 30 Hz, with a dynamic range of about 72 dB (30 dB on the tape plus 42 dB for seven 6-dB gain steps). Although the POB's worked fairly well, the ambient noise was often high, and signals were sometimes monochromatic in character. After some investigation, the high noise was attributed primarily to ocean-bottom currents strumming the high-profile, inverted-pendulum package, and to coupling between mechanically noisy tape-drives and the seismometers housed in the same pressure case. The monochromatic signals were attributed to poor coupling between the POBS package and the bottom.

These problems were rectified to some extent in a new design called the "isolated sensor OBS" or ISOBS. The electronics and recovery systems in this design were nearly identical to those in the POBS. The seismometers, however, were deployed in a separate small pressure case that was mechanically decoupled from the rest of the ISOBS (Fig. 1). This configuration eliminated tape recorder noise and greatly reduced current strumming noise. And although coupling between the seismometers and the ocean-bottom was improved, it still remained a significant problem. The ISOBS instruments were in use until 1987. A more detailed summary of the POBS and ISOBS design characteristics has been written by Byrne et al. (1983).

Ocean Sub-bottom Seismometer (OSS)

HIG began development of the ocean sub-bottom seismometer in 1978, and between 1979 and 1982 four OSS deployments were made from the D/V Glomar Challenger at sites in the Pacific and Atlantic. Technical problems limited the amount and quality of data from the first three OSS's. OSSIV, however, had high-quality, real-time seismic data during deployment, high-quality, long-term recorded data during the first two-month remote operating period, and high-quality, real-time data during recovery and redeployment. OSSIV was (and still is) located down Deep Sea Drilling Project Hole 581C near the Kuril Islands in the northwestern Pacific, with 60 days of data waiting to be recovered. Water depth at the site is 5467 m, and the sediment cover is 357 m on top of basement basalts. The OSSIV sensor package was deployed in the sediment just above basement. Data from

OSSIV, and from OBS's deployed nearby during the deployment period are discussed later.

A general diagram of the deployed OSS system is given in Fig. 2. The borehole sensor package contains geophones stacked along three axes, a temperature sensor, a 2-component tiltmeter, and floating point analog-to-digital electronics. It is clamped inside the drillhole by a remote controlled extension arm. The data are transmitted in digital format up an electromechanical cable to a recorder package suspended above the bottom nearby. The recorder package converts the digital seismic data back to three analog signals for recording on 4-channel, slow-speed, analog cassette tape recorders similar to those used in the HIG OBS's. The temperature and tilt data are encoded in a time code signal and recorded on the remaining tape channel. Five tape recorders provide the capability to record continuously for up to 66 days with frequencies up to at least 30 Hz. Attached to the recorder package is a long, positively-buoyant, polypropylene rope that can be grappled for as a backup recovery procedure. (The excess positive buoyancy of this rope suspends the recording package above the bottom.) At the far end of the rope is the primary recovery system. It consists of an anchor assembly, recovery buoy, and two redundant acoustic releases.

The OSS system must be deployed by a drillship. The sensor package (tool) is lowered from the drillship through the drillstring (positioned above the bottom of the hole) using electromechanical logging cable. When the tool is at the proper depth it is clamped in position by remote command and tested for proper operation. Then the cable is cut and the drillstring is stripped off around the cable by a special procedure. At this point, real-time recording of the digital sensor signals can be made onboard the drillship, and active seismic experiments can be conducted. For final deployment, the recording package, recovery system, and anchor are attached and deployed over the side. Data recovery is accomplished at a later time using a standard research ship. An acoustic signal is sent from the ship to the acoustic releases, causing the anchor to be released and the recovery buoy to float to the surface. If this doesn't work, the polypropylene rope is grappled for. The recording package can then be pulled up from below and brought onboard. Tapes and batteries can be replaced; real-time experiments can be performed; and the recording system redeployed without disturbing the tool. If removal of the tool is desired, it can also be pulled out of the hole, although this is risky since the electromechanical cable may break if the tool gets stuck. A more complete description of the OSS system -- its specifications and procedures for deployment and recovery -- is given in a report by Harris et al. (1988).

Wake Island Hydrophone Array (WIA)

The Wake Island Hydrophone Array is an array of twelve hydrophones located near Wake Island in the northwestern Pacific Ocean (Fig. 3). Six of the hydrophones are on the ocean bottom at 5.5-km depth, at the center and vertices of a 40-km-wide pentagon located approximately 100 km to the north of Wake. The other six hydrophones are located at three sites to the south and west of Wake and are at the depth of the SOFAR (SOund Fixing and Ranging) channel axis at about 0.8-km depth. The entire array spans an area that is about 100 by 300 km. The hydrophones are passive, moving-coil type, and signals from the hydrophones are transmitted to Wake via long undersea cables. The array was installed in the late 1950's as part of the US Missile Impact Location System, but it was abandoned by that project after many years of use. Since 1976, HIG has been using the array to record seismic signals. In 1982, a digital recording system was installed to record signals from eight of the WIA hydrophones (five bottom, three SOFAR) on a continuous basis. This recording system is still in operation, and the reduced data, consisting primarily of ambient noise samples and time intervals containing seismic signals from earthquakes and

explosions, are stored at HIG and at the DARPA Center for Seismic Studies in Rosslyn, Virginia.

ADVANTAGES AND DISADVANTAGES OF LOCATING SENSORS AT DIFFERENT DEPTHS WITHIN THE OCEAN-SEDIMENT-BASEMENT COLUMN

SOFAR Depth

The SOFAR channel is a low-velocity zone in the water column that acts as a very efficient acoustic waveguide. It is found in all the world's oceans, and its axis is generally at a depth of 1 km or less. Sound waves within this channel can propagate with little loss over thousands of kilometers. Seismic measurements near the SOFAR channel axis can be made using hydrophones suspended above deeper ocean floor, or using seismometers (or hydrophones) deployed on seamounts that rise to axis depth.

The primary advantage of locating sensors at SOFAR channel depth is the abundance of long-range water-borne signals that will be observed. Using an array of SOFAR hydrophones in the Pacific (including the WIA SOFAR hydrophones), Duennebie and Johnson (1967) located 6.5 times more northwestern Pacific earthquakes than were located during the same one-year period by the worldwide seismic network. SOFAR sensors can detect signals from events other than earthquakes -- for example, submarine volcanoes and nuclear test explosions. MacDonal Volcano at the southeast end of the Austral seamounts was discovered by triangulating on underwater sounds produced by its eruptions (Norris and Johnson, 1969), and underwater volcanism from Kaitoku Seamount was observed by Walker et al. (1985) using WIA SOFAR hydrophones. Extremely strong acoustic signals are also routinely recorded at WIA from French nuclear test explosions at Mururoa Atoll, more than 10,000 km away (McCreery and Walker, 1988). One of the important advantages of recording water-borne signals is that they travel quite slowly (1.5 km/sec) compared to the phase velocities of the other oceanic short-period phases P, Po, or So. This property makes it somewhat easier to locate distant events with small arrays, since time offsets between sensors are relatively large.

The primary disadvantage of locating sensors at SOFAR depth is high noise. The same properties that make the channel efficient for transmitting signals also make it efficient for transmitting noise. The primary noise sources in the frequency band from 1-30 Hz are ocean surface wind waves and shipping. Other noise is produced by scientific and military underwater explosions, and by biological sources such as whales. Signals from even small explosions can propagate in the SOFAR channel over an entire ocean. A typical one-day helicorder record of a WIA SOFAR hydrophone (Fig. 4) has many tens of discrete signals, most of unknown origin. Figure 5 from McCreery (1988) shows a comparison between the one-year-average ambient noise on four WIA hydrophones, two at 5.5-km depth (74 and 76) and two at the SOFAR axis depth of 0.8-km (10 and 20). It is clear that the SOFAR hydrophones are increasingly noisy towards the high frequencies. This additional noise impairs the SOFAR hydrophone's ability to detect small P, Po, and So signals that are more easily observed on ocean bottom sensors. The excess noise of hydrophone 10 relative to hydrophone 20 is due to hydrophone 10's proximity to the Wake shoreline, a topic that will be discussed later in this report.

Deep Ocean Seafloor

Extensive measurements of signal and noise on the seafloor in deep ocean using OBS's and using the deep WIA hydrophones have been made at HIG. There are many

advantages to taking measurements on the deep ocean floor including: (1) low ambient noise at frequencies above 3 Hz, (2) a high level of separation between transverse and longitudinal components of seismic phases refracted from basement or below, (3) the relative ease of instrument deployment and recovery, and (4) the large number of flat deep-ocean-basin sites (>40% of earth's surface at depths >4000m). Some disadvantages associated with deploying instruments on the deep-ocean floor are: (1) high ambient noise levels around 1 Hz, the dominant frequency of teleseismic P, (2) difficulty in achieving good coupling between the seismometers and the sediments, and (3) ocean-bottom-current induced noise, especially on the horizontal seismometers. A more detailed discussion of these factors follows.

Figure 6 shows some ambient deep ocean noise spectra compared to average continental noise. It can be seen that ambient deep ocean noise is relatively high at frequencies around 1 Hz, but relatively low at frequencies above 3 Hz. For this reason, the deep ocean is a good place to detect seismic signals that are rich in high frequency energy. These include oceanic lithosphere phases Po and So, teleseismic P from deep-focus earthquakes, and teleseismic P from nuclear test explosions. Conversely, the deep ocean bottom is generally a poor place to detect short-period mantle-refracted P from shallow-focus earthquakes, since the dominant frequency of those phases is around 1 Hz where noise levels are high.

Urlick (1986) plotted noise levels at several discrete frequencies as a function of depth, and the noise clearly decreases with depth below the axis of the SOFAR channel. But perhaps the most important feature of these curves is that the noise decreases most rapidly below critical depth. Critical depth is the depth of the lower boundary of the SOFAR channel -- the depth at which the acoustic velocity equals the maximum velocity at the upper boundary of the SOFAR channel, near or at the surface. Critical depth can vary from less than 1 km at latitudes greater than 60 degrees, to more than 4 km at mid and low latitudes. Critical depth near Wake is approximately 5 km, and the WIA deep hydrophones at 5.5 km are below this threshold. Although a long-term systematic study of seismic noise levels at different ocean depths has not been made, it would appear from the Urlick data that it is important to site the seismic sensors as deep as possible, preferably below critical depth, to minimize noise.

Figure 7, from Duennebier et al. (1987a), shows some ISOBS refraction data recorded in the northwestern Pacific in 1982. The ISOBS was deployed in 5500 m of water, and rested on top of approximately 350 m of pelagic sediment. A striking feature of these data is their high quality, and also the clear separation of compressional and shear arrivals. The hydrophone record mainly shows refractions that are compressional at the instrument, with almost no hint of shear arrivals. Conversely, the horizontal record mainly shows refractions that arrive as shear energy, with almost no hint of compressional arrivals. The vertical record is most like the hydrophone record, but with some low-amplitude shear arrivals. Cross coupling in the sensor package between horizontal and vertical signals that correspond to shear arrivals on this record. These data clearly illustrate one advantage of sensor placement on (or possibly within) ocean bottom sediments. Low sediment velocities force arrivals coming up from basement to propagate nearly vertically, thus compressional motions are in the vertical direction and shear motions in the horizontal direction. This allows for their easy identification on records such as these with vertical and horizontal sensors. The data also illustrate that OBS data can be very high quality, with high signal-to-noise and signal fidelity on all components. Our experience indicates that the primary reason why most OBS data are not of this high quality is that they are usually poorly coupled to the sediments and that they are often noisy due to the instrument vibrations in bottom currents.

Below the Seafloor

Measurements of signal and noise in sediments below the seafloor have been made using the HIG OSS. These measurements show that the primary advantages of deploying seismic sensors below the ocean-sediment interface are higher signal fidelity and lower noise. The data do not show, however, just how deep into the sediments it is necessary to go in order to achieve these gains. The main disadvantage of siting sensors below the seafloor is the greatly increased complication and expense of a drillhole deployment compared to an ocean bottom, OBS-type deployment. This disadvantage might be reduced considerably if it was only necessary to implant the seismometers a short way into the sediment using a method that did not require either a drillship or an old drillhole.

Improved signal fidelity below the ocean-sediment interface is due primarily to improved coupling between the seismometers and the sediments. Figure 8 shows a diagram of the OSS tool deployed down a drillhole and locked into position. The lever arm has been extended by remote control from the drillship, and the sensor package is firmly locked against the side of the drillhole, ensuring that the seismometers are well coupled to the sediments. Figure 9, from Duennebier et al. (1987b), is a 43-minute, rectified, 3-component record of noise produced by a ship passing near OSSIV. This figure illustrates the general fidelity of particle motion that is recorded by the OSS. The signal envelope for the vertical sensor record has one central peak, and the envelopes for the two horizontal sensors are doubly peaked. These features are predicted by a simple computer model of the data envelopes for a ship passing nearby at an oblique angle to the horizontal seismometer axes. Vertical motions are largest when the ship is closest to the array. Horizontal motions are largest when the ship is located in line with the seismometer axis. In the data, maxima for the two horizontals are at different times as expected, and they straddle the maximum for the vertical as expected. Thus, the OSS appears to be yielding accurate particle motion data. Figure 10, from Duennebier (1987), shows arrivals from a magnitude 7.8 earthquake in Japan recorded by OSSIV at 15.7 degrees epicentral distance. The broad range of frequencies recorded (11 octaves) and the unique character of each trace are a strong indication that the OSS sensors are well coupled to their surroundings. What these combined data show is that a seismometer located below the ocean-sediment interface can be effectively coupled to the sediments by a fairly simple mechanical design, and can thus be used for recording accurate particle motions. They also illustrate some of the interesting seismic data that can be studied in the oceans when the sensors are well coupled to the surrounding material.

Reduced noise levels are also observed below the seafloor. Figure 11, from Duennebier et al. (1987b), is a comparison between ambient noise spectra recorded simultaneously on the vertical and horizontal components of OSSIV and a nearby ISOBS. The general similarity in shape of the two vertical spectra indicates that noise sources are essentially the same, however, noise levels down the hole are 20-30 dB lower than those on the ocean bottom. A correction for impedance differences between the sediment down the hole and at the surface can only account for only a few dB of this separation at most. On the horizontal components, the ISOBS spectrum and the two OSS spectra are generally dissimilar in shape, indicating that their respective noise sources are probably not the same. Horizontal noise levels are 30-40 dB less down the hole. More than 15 dB of this separation may be due to the large impedance difference caused by extremely low shear velocities at the top of the sediments (0.05 km/sec are typical). A limited study of nearby, unreported earthquakes recorded by OSSIV and several ISOBS's during different time periods (Cessaro, 1987) appears to indicate an increased sensitivity of approximately one magnitude level on OSSIV compared to the ISOBS's. This implies that OSSIV had a signal-to-noise improvement of around 20 dB over the ISOBS's for signals propagating up from below, approximately the same as the reduction in noise. Thus, it appears that

significantly reduced noise levels, and correspondingly increased signal-to-noise levels for signals arriving from below, can be found below the ocean-sediment interface.

REGIONAL SOURCES OF AMBIENT NOISE THAT CAN BE AVOIDED

An important factor to consider in determining future regional sites for the deployment of long-term seismometers in the oceans is excessive or extraneous ambient noise. Just as it is important to choose a quiet site for a land seismic station, away from roads, streams, machinery, and high wind, it is important to choose a quiet site in the ocean. Many sources of ambient ocean noise have been identified, and most of them can be avoided to some extent by careful siting.

High Winds (or High Wind-Driven Ocean Waves)

Ambient deep-ocean noise levels at frequencies from at least 0.5 to 30 Hz are strongly related to windspeeds on the ocean's surface. This relationship is evident from a study of ambient noise spectra on WIA hydrophone 74 and corresponding winds measured at Wake Island (Figure 12 from McCreery, 1988). The data were averaged from three-minute-long ambient noise samples taken once every six hours over a one-year period. From 0.5 to 6 Hz, they show that ocean-bottom noise increases regularly with increasing windspeed until a clearly defined saturation level is reached. However, the noise level variations and saturation are probably the more direct result of corresponding variations and saturation of waves on the ocean surface driven by the wind. The maximum variation in ambient noise with windspeed is 20 dB (a factor of 10) at around 1 Hz. Thus, a significant increase in the detectability of teleseismic P, with its dominant frequency at around 1 Hz, is possible in low-wind (low-wave) conditions at Wake. These data suggest that it should be possible to maximize the sensitivity of future ocean seismometers by choosing sites with low mean windspeeds. Many oceanic regions with low mean windspeeds exist (Figure 13) from McCreery, 1988), primarily at low latitudes, and they may be the quietest sites on earth for the detection of short-period seismic signals.

Coastlines

Ocean waves breaking along coastlines can be a significant source of ambient ocean noise. A comparison between the one-year-mean noise spectra of two WIA SOFAR hydrophones (Fig. 5) illustrates this point. Hydrophone 10, located only 3 km to the south of Wake, is 5-10 dB noisier at all frequencies (0.1-30 Hz) than hydrophone 20, located 200 km to the south of Wake in open ocean. In addition, the variation of the noise with windspeed is much different on hydrophone 10 compared to hydrophone 20 that is more similar to the deep hydrophones 74 and 76. Wake is a very small coral atoll with a radius of only about 2 km. For longer shorelines such as those on the edge of continents, the increase in noise may be significantly more pronounced. Additional measurements need to be made in order to quantify the levels and extent of this extraneous noise. It is clear, however, that sites near coastlines should be avoided whenever possible.

High Bottom Currents

Bottom currents can create at least two separate types of ocean noise: (1) noise caused by direct interaction of ocean-bottom sensor packages with the current, and (2) noise caused by current-induced turbulent pressure fluctuations on the ocean floor. The first type of noise was a problem for many years with the HIG POBS. The POBS package, with its sensors inside, had a small anchor on the bottom and floats on the top. It was an inverted pendulum that rocked back and forth in the current. In addition, the antennas for the recovery radio transmitters vibrated whenever currents swept by them.

These extraneous motions were picked up by the sensors, and often they masked signals of interest. This problem was solved to some extent in the ISOBS design by making a separate low-profile sensor package and isolating it from the recorder and recovery systems. However, current noise of this type is still occasionally seen on the ISOBS. Any type of burial of the sensor package should eliminate this noise. The second type of noise is present most notably on horizontal sensors. When a current-induced cell of turbulence passes over the ocean bottom, it can create tilts due to the pressure differences on opposite sides of the cell. These tilts manifest themselves as horizontal accelerations due to corresponding changes in the gravity component as the sensor is tilted. This type of noise is more carefully described in a paper by Webb (1988). Although this type of noise can be a significant problem on the ocean floor, it can probably be reduced to negligible amounts by burying the sensor package a few meters (the turbulent cell dimension) below the interface. Additional data will be required to verify this solution. In any case, it is probably best to avoid siting ocean seismometers in regions with high bottom currents.

Shipping Lanes

Surface ships are a considerable source of noise in the ocean, even at frequencies from 1-30 Hz. Data from the WIA hydrophones, located far from commercial shipping lanes, are nevertheless contaminated by a significant amount of shipping noise. Over a one-year period, the data from WIA hydrophone 74, at 5.5-km depth, were found to be contaminated by shipping noise in varying amounts that increased regularly with the signal frequency (Figure 14). At 1 Hz, only about 1 percent of the data are contaminated, but at 20-30 Hz nearly 8 percent are contaminated. This contamination would be much worse near any shipping lane. And although the multiple narrow-band noise typically produced by a ship may be removed to some extent by careful filtering, it can prevent many types of modern signal analysis that require exact waveform data or spectral analyses of broadband signals. Thus, the level of shipping traffic should be given careful consideration before choosing a site for an ocean seismic station.

Hurricane and Typhoon Lanes

Although the low latitudes are generally advantageous for reducing noise because of low mean windspeeds, they can sometimes be disadvantageous because of the occurrence of hurricanes and typhoons. These severe storms produce locally high levels of noise at 1 Hz and above due to their high windspeeds and subsequent high waves as described above. In addition, they can produce high noise levels at frequencies of 0.2 Hz and below that propagate to a radius of a thousand kilometers or more (Figure 15). Since hurricanes and typhoons often form and travel within certain known lanes, it is prudent to avoid these lanes if possible.

Whale Migration Routes

Some unusual noises that appear regularly in the data from WIA are high-amplitude pulses, one or two seconds in length, that repeat every 20-30 seconds. They have frequencies ranging from 17-20 Hz, with signal-to-noise ratios often many tens of decibels, and the pulses sometimes continue for many days. They are present most often between February and April, but are seen during the rest of the year as well. These signals are presumed to be from whales, and they have been observed in many regions of the Pacific. This noise is above the frequency range of teleseismic P, but not above the range of oceanic seismic phases Po, So, or T, and not above the range of explosive seismic data. It may therefore interfere with those types of signals to some extent. Migration routes for these whales should be avoided if signals in the 17-20 Hz band are to be recorded and studied.

SUMMARY

Many factors should be considered in the design and siting of long-term, broadband seismic instrumentation in the oceans. Sensors located in the SOFAR channel are ideal for detecting energetic waterbourne signals at long distances. Sensors located on the ocean bottom are more sensitive to refracted signals such as P because of reduced noise, especially if the bottom is below the SOFAR channel. But noise on the ocean deep bottom may still be high if the sensor package is exposed to currents, and poor coupling of the sensors to the sediments may severely degrade the recorded particle motions. Careful design of the sensor package, and possibly a shallow burial of the sensor package should greatly reduce or eliminate these problems. Drillhole sensors located far below the water-sediment interface have clear advantages in terms of signal-to-noise ratios and coupling, but the cost of deployment is very high. Sensors should be located in regions that minimize the sources of extraneous ambient noise. These sources include: (1) high winds, (2) coastlines, (3) high bottom currents, (4) shipping, (5) hurricanes, and (6) whales.

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FIGURE CAPTIONS

Figure 1. The ISOBS isolated sensor package deployment. (A) The ISOBS at the end of its free-fall to the ocean bottom. (B) After a few hours, a magnesium-wire release activates, and the sensor package is pushed by an elastic cord away from the rest of the ISOBS. (C) The sensor package free falls away from the main package, pivoting on a hinge bar. At an angle of about 60 degrees, the hinge bar is restrained by a small wire and the sensor package tumbles free. (D) The ISOBS in its fully deployed configuration.

Figure 2. The various components of a deployed OSS system include: (A) the sensor package locked in the drillhole, (B) an electromechanical data transmission cable, (C) recorder package, (D) positively buoyant recovery rope, (E) recovery buoy, (F) anchor, and (G) recovery ship.

Figure 3. Location map for hydrophones of the Wake Island Array.

Figure 4. A typical section of helicorder record from a SOFAR channel hydrophone. This particular record was made on June 26, 1988 from Wake hydrophone 10. The time between tic marks is one minute, and the time between adjacent lines is 30 minutes.

Figure 5. The one-year mean noise spectra of Wake hydrophones 76, 10, and 20 plotted relative to the one-year mean noise spectrum of hydrophone 74 (zero dB).

Figure 6. Ambient deep-ocean noise spectra for the Wake Island Array (WIA) hydrophones 74 and 20, for a hydrophone bottomed off Eleuthera Island at 1200 m depth, and for a hydrophone bottomed off Bermuda at 4300 m depth (Bermuda and Eleuthera data from Nichols, 1981). Also shown is average continental seismic noise (Brune and Oliver, 1959), and a very quiet continental noise measurement at Lajitas, Texas (Herrin, 1982).

Figure 7. ISOBS data from an airgun line off of the Kuril Islands. Data from the three different sensors of the ISOBS -- hydrophone (a), vertical (b), and horizontal (c) -- are shown. Arrivals "C" and "G" are respectively the direct and first-multiple water-wave arrivals. Arrivals "A" and "B" are crustal P and S phases, respectively, that arrive at the ISOBS as a compressional energy through the sediment. Arrivals "D" and "E" are crustal P and S phases, respectively, that arrive at the ISOBS as shear energy. Arrival "F" is a basement reflection that has converted from compressional to shear at the sediment/basement interface.

Figure 8. The OSS borehole sensor package (tool).

Figure 9. Signal from a ship passing nearby to OSSIV. Smoothed and unsmoothed rectified traces of the signal at 20 Hz are shown for the E-W, N-S, and vertical components. The smooth curve shows the theoretical amplitude function for a ship on a course of 120 degrees at a speed of 30 km/hr.

Figure 10. The 26 May 1983 Japan earthquake recorded by the OSSIV geophones. The spiky arrivals before the earthquake are from small explosive charges.

Figure 11. A comparison between simultaneous noise levels recorded by OSSIV, by a nearby ISOBS, and by an Oregon State University (OSU) ocean bottom seismometer. On the left (a) are the vertical components and on the right (b) are the horizontal components.

Figure 12. The average noise spectra of Wake hydrophone 74 for eight windspeed ranges (from McCreery, 1988). Noise levels increase regularly with windspeed at all frequencies, and two types of noise are observed. The first noise type, between about 0.5 and 6 Hz, increases with windspeed until a saturation level (arrowhead) is reached. The second noise type, from about 4 Hz to more than 30 Hz, increases with windspeed for winds above 12-16 mph.

Figure 13. Eighty-year-mean ocean-surface windspeed compiled by the University of Hawaii's Department of Meteorology (from McCreery, 1988). The contour interval is 1 m/s (2.24 mph), and shaded regions have mean windspeeds less than 4 m/s (8.95 mph). The one-year-mean windspeed measured at Wake is 6.26 m/s (14 mph).

Figure 14. The percent of noise samples over a one-year period on Wake hydrophone 74 that were contaminated by shipping noise, plotted as a function of frequency (from McCreery, 1988). The feature at 20 Hz is an artifact due to a 60 Hz aliased signal in the original data.

Figure 15. Spectra from Wake hydrophone 74 during the passage of Typhoon Owen. Noise levels at 0.13 Hz were highest on 21 October, when the typhoon had sustained winds of 100 kts but was still more than 1000 km from Wake. Noise levels at frequencies above 0.2 Hz were highest on 24 October, when Owen made its closest approach to Wake (about 500 km) with windspeeds of 50 kts. Velocities noted by each spectrum are the daily-mean windspeeds at Wake.

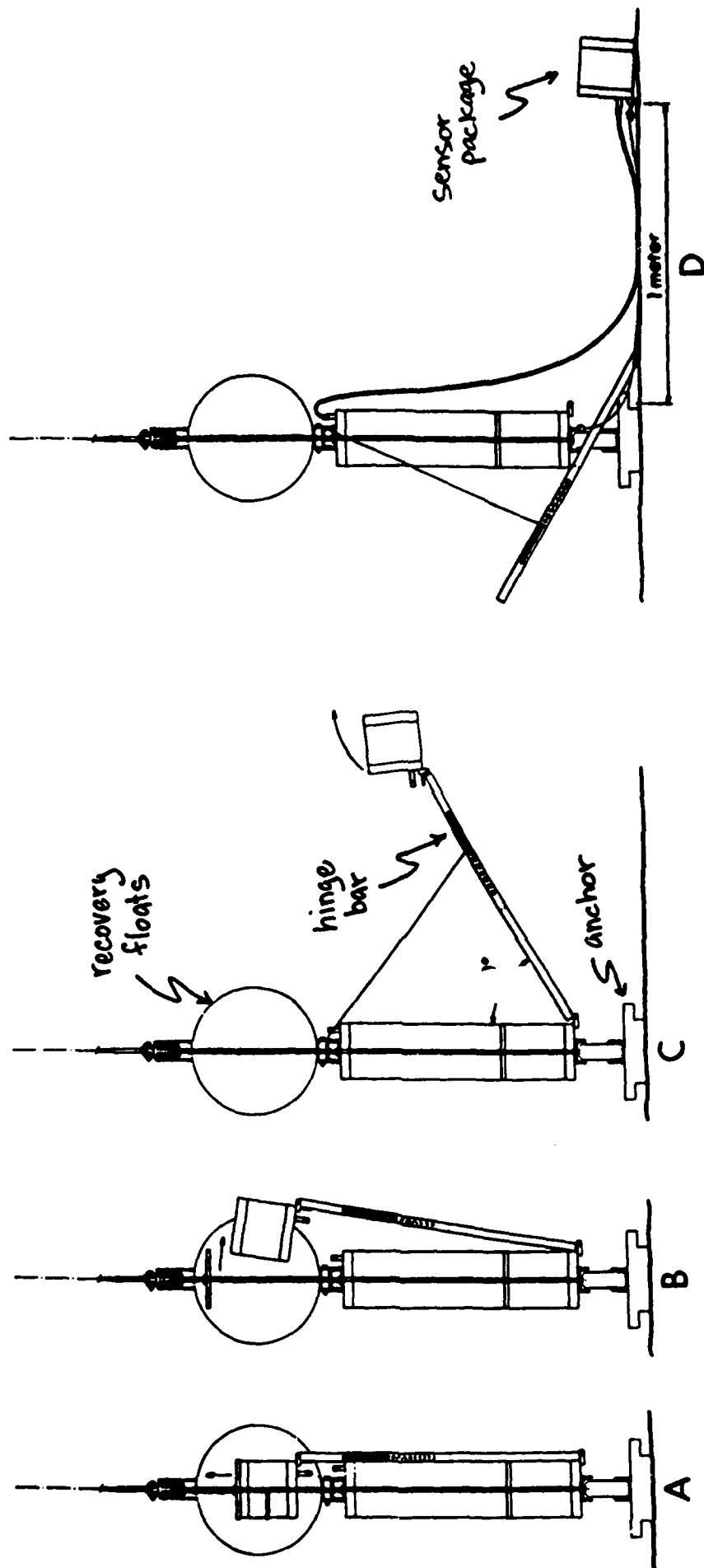


Figure 1

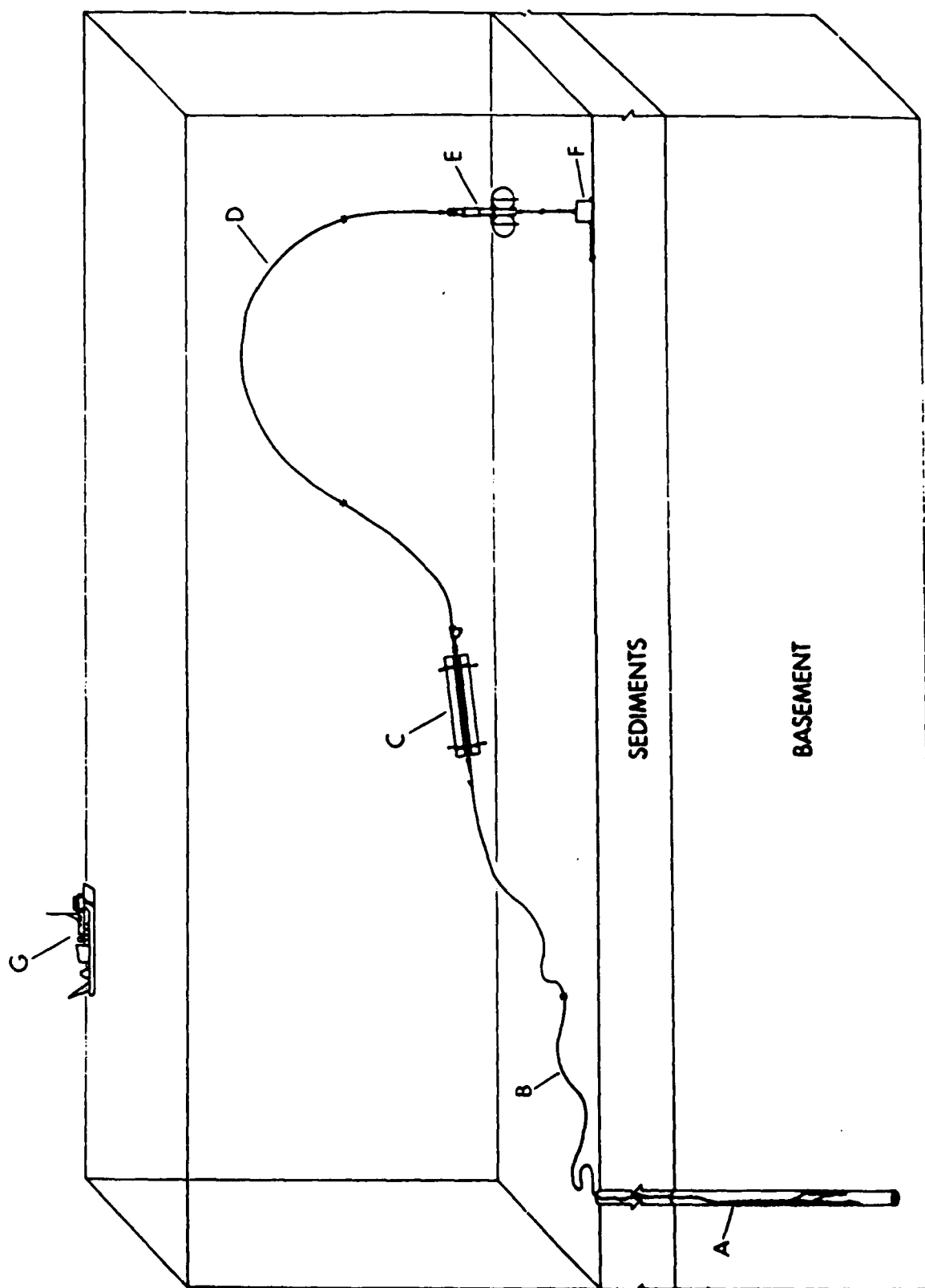


Figure 2

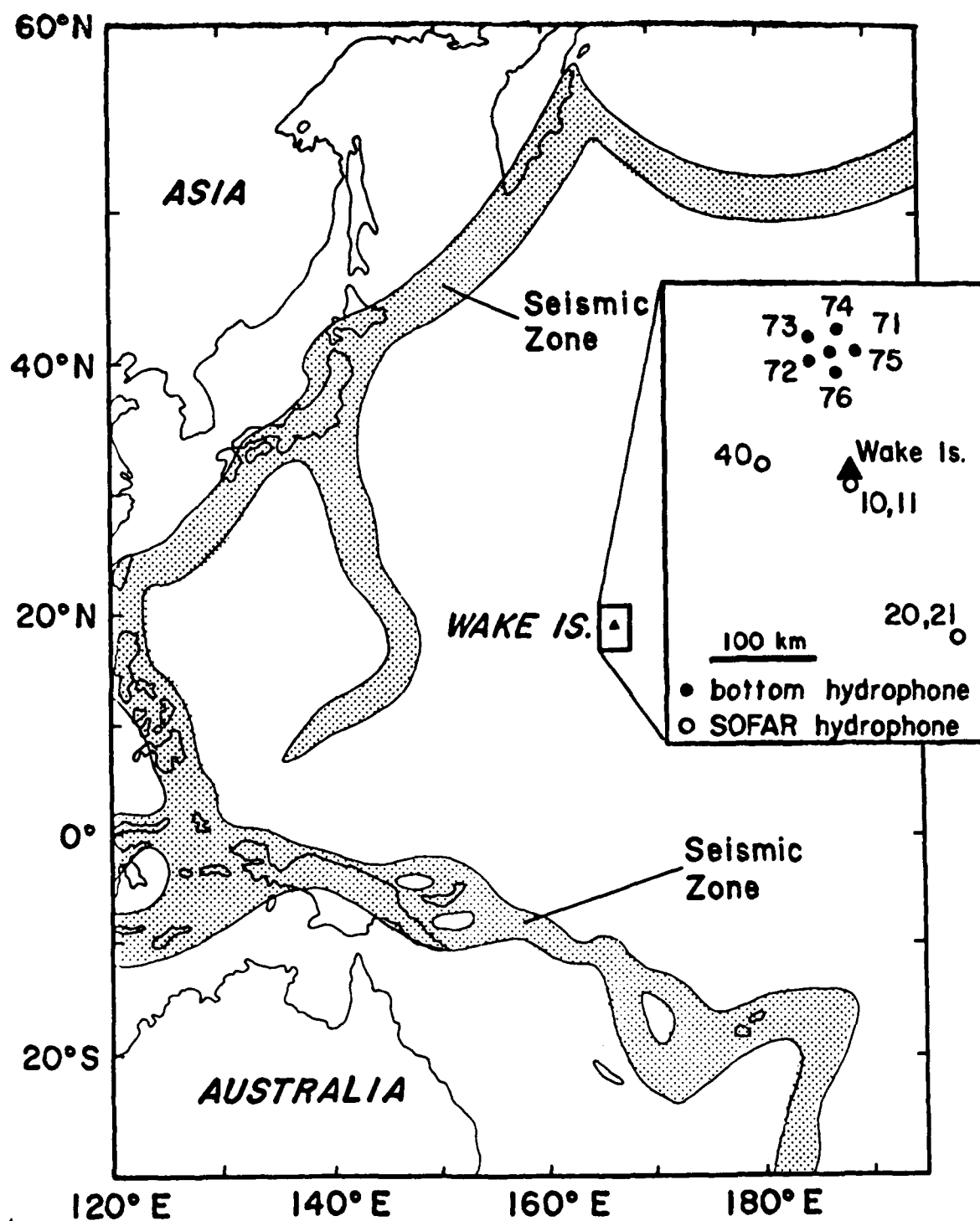


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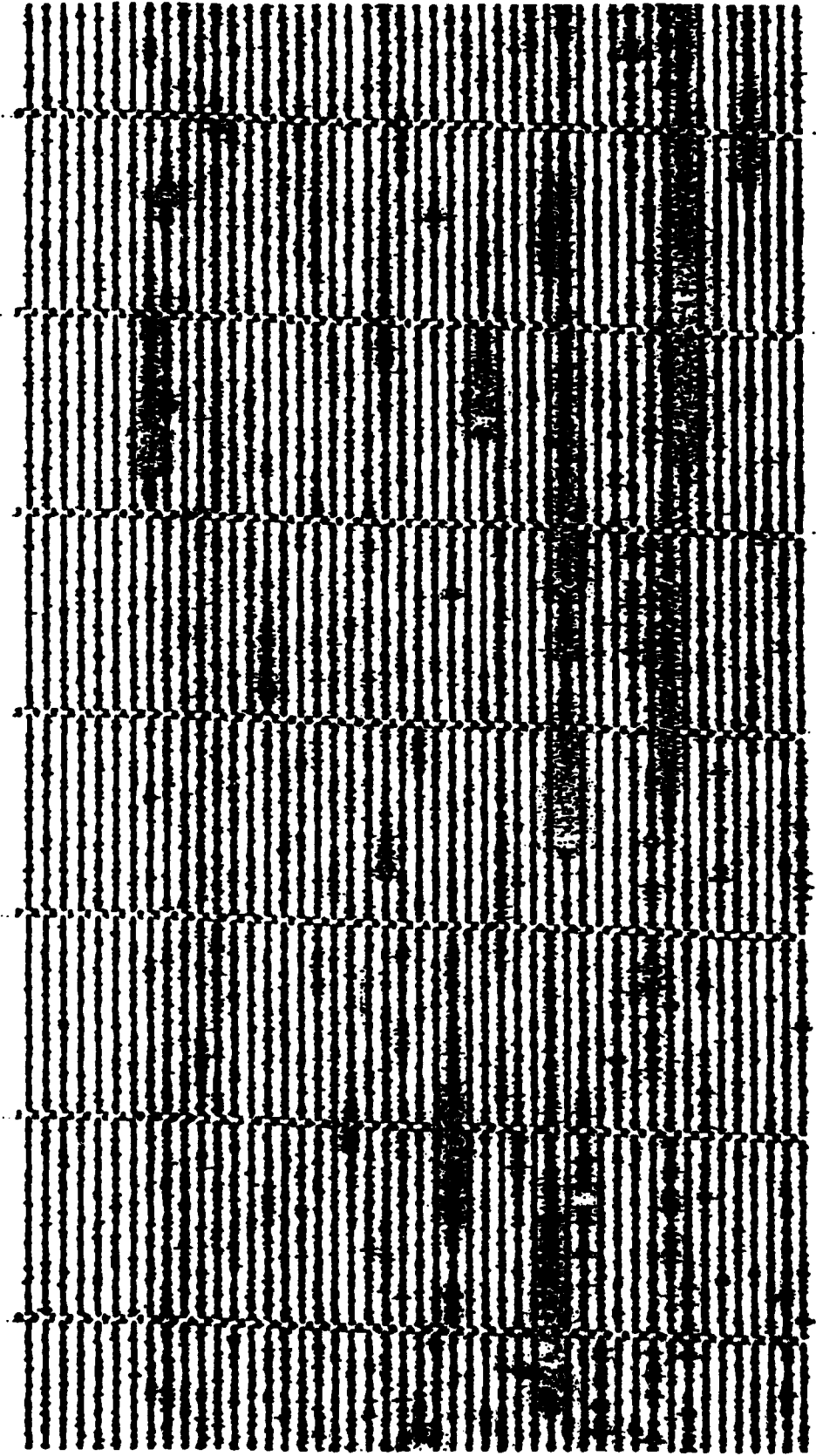


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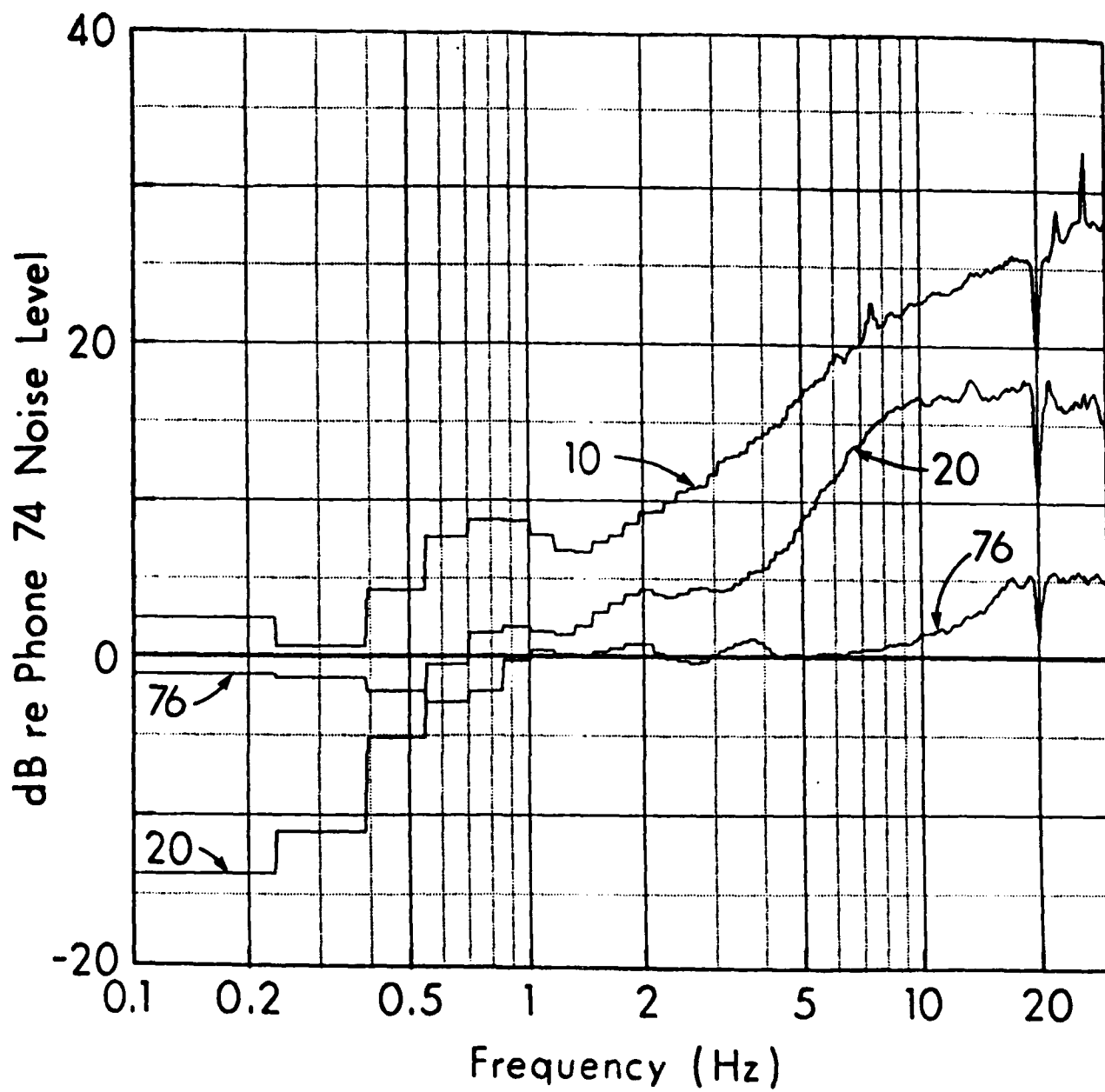


Figure 5

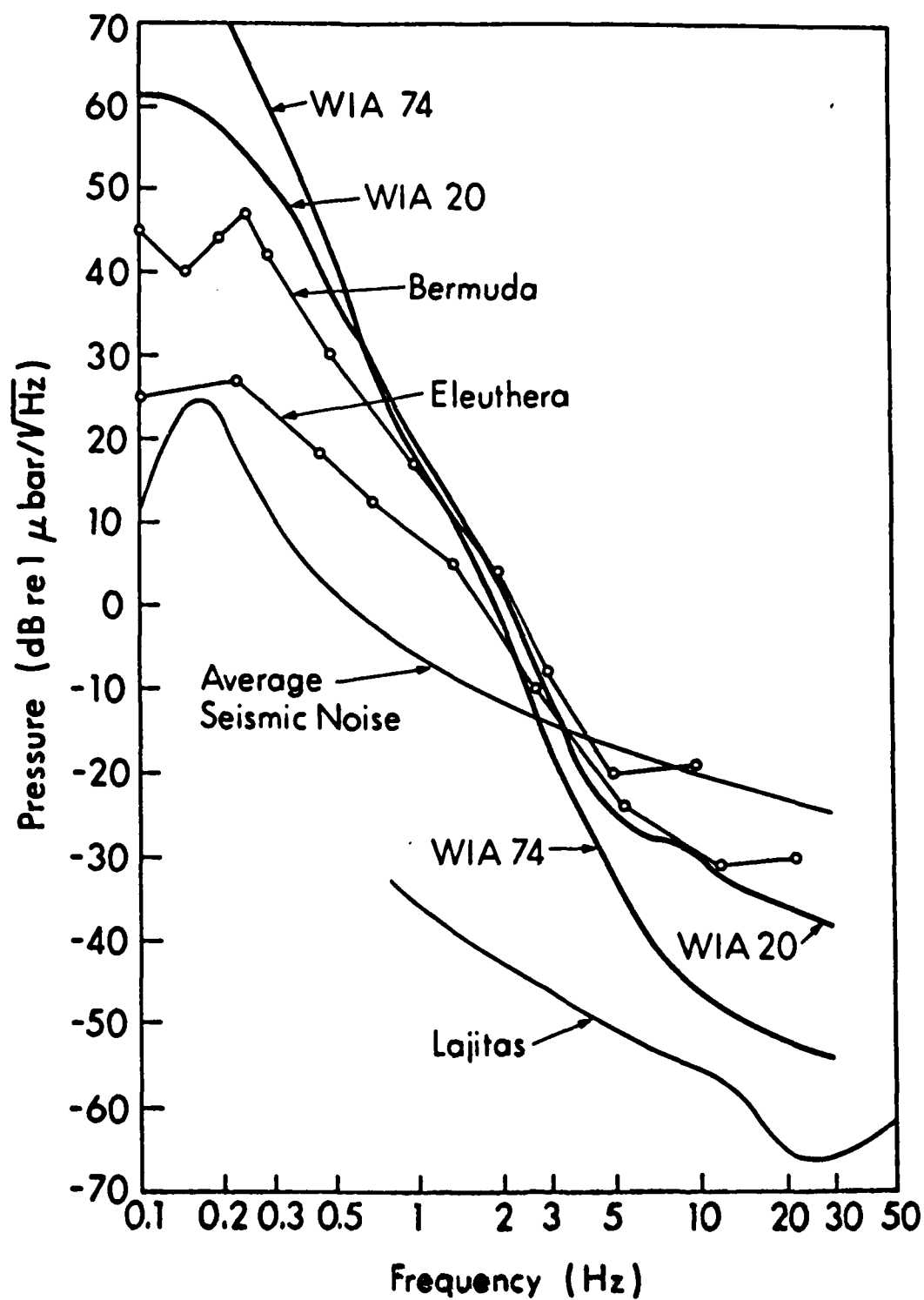


Figure 6

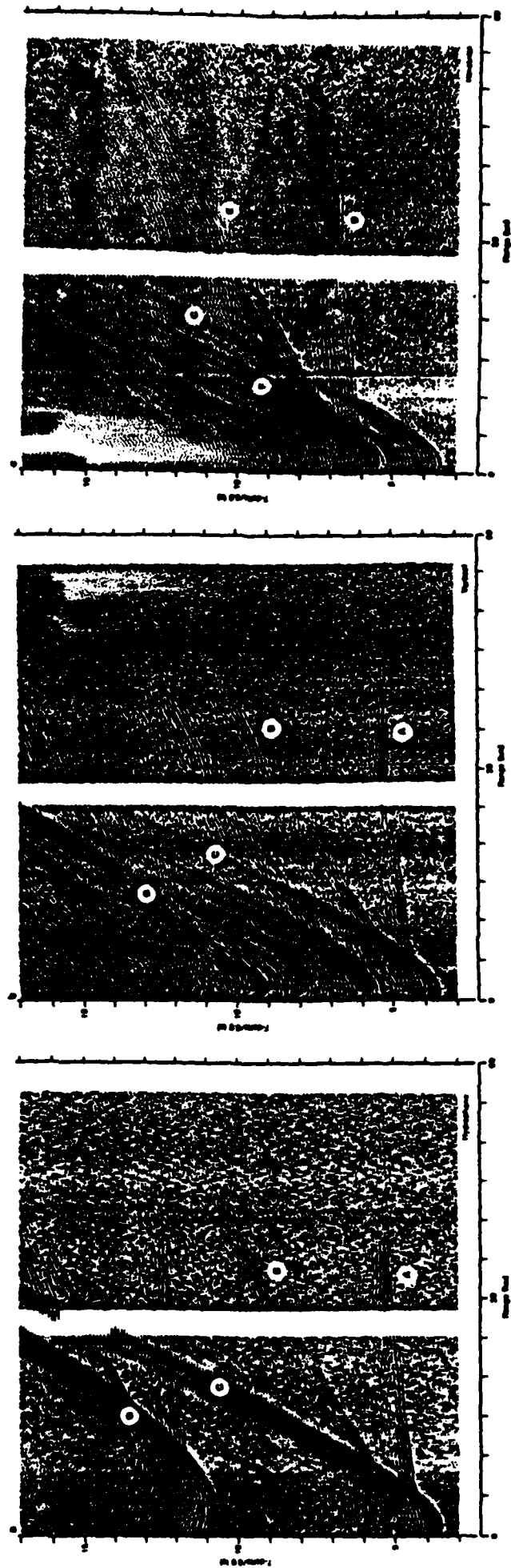
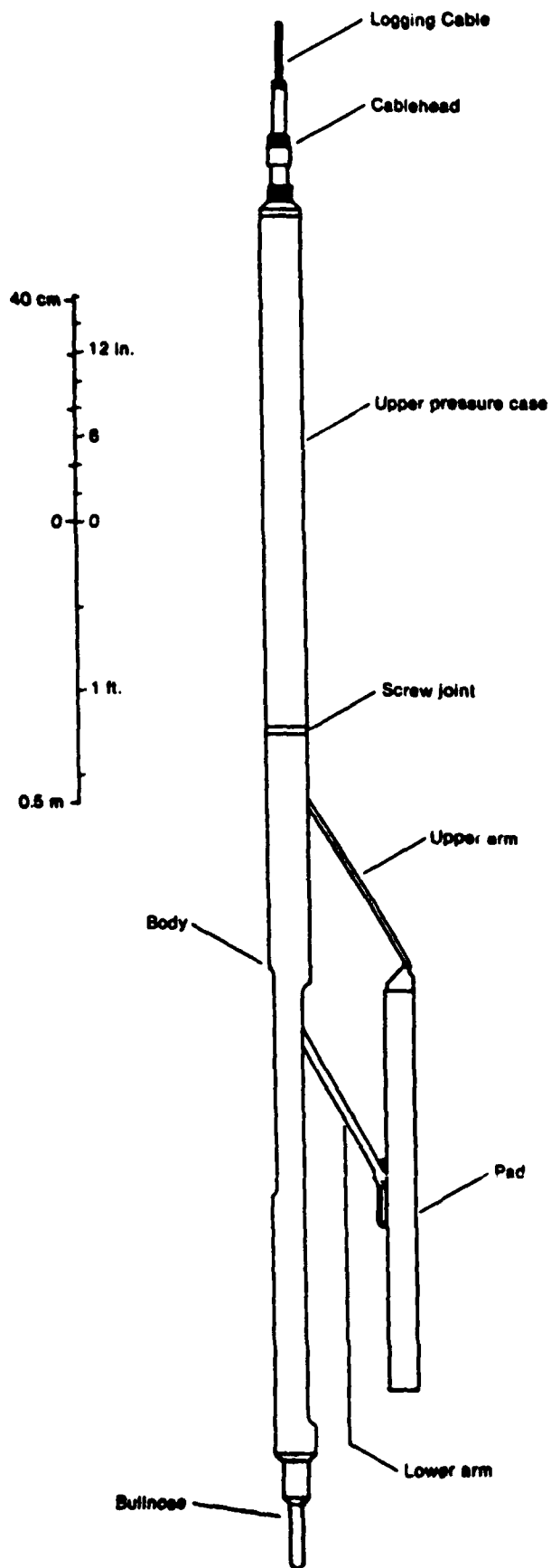


Figure 7



Borehole package (tool) as installed on OSS IV.

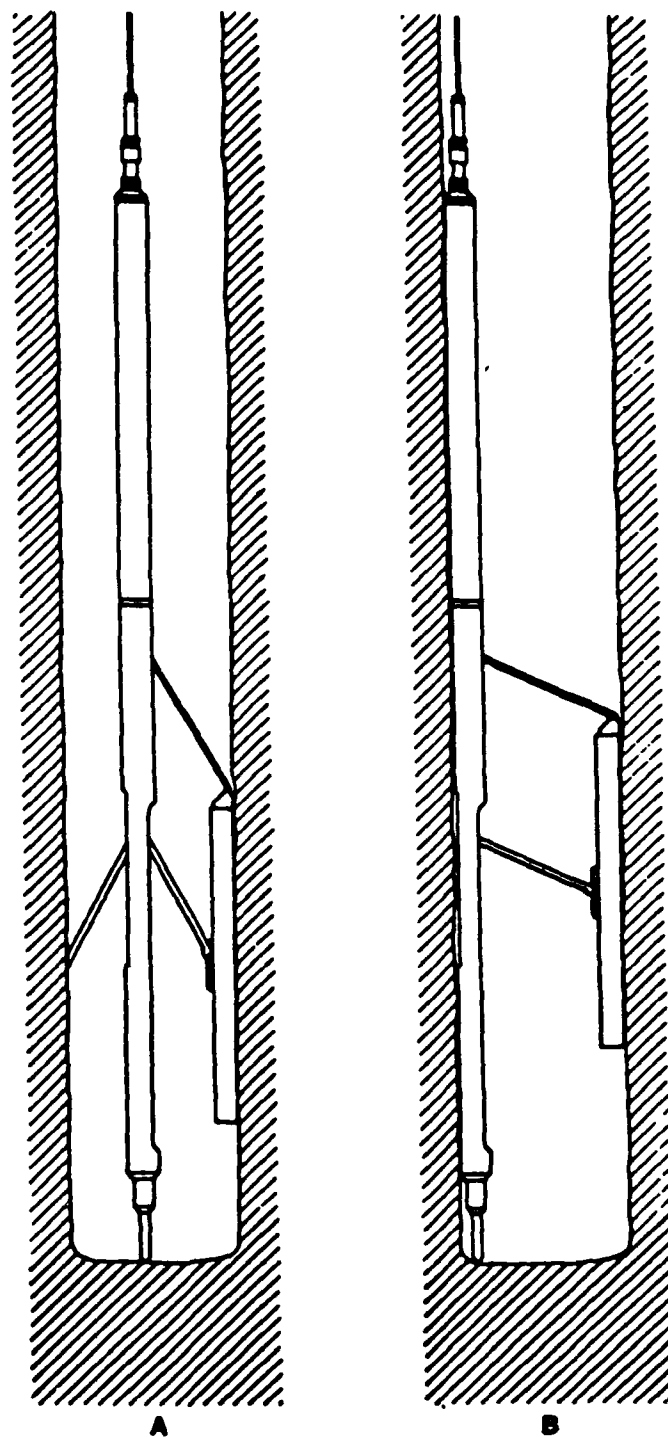


Figure 4 Modification of borehole package. A. Original package as supplied by Gearhart Industries. B. HIG modification to improve seismic coupling to borehole.

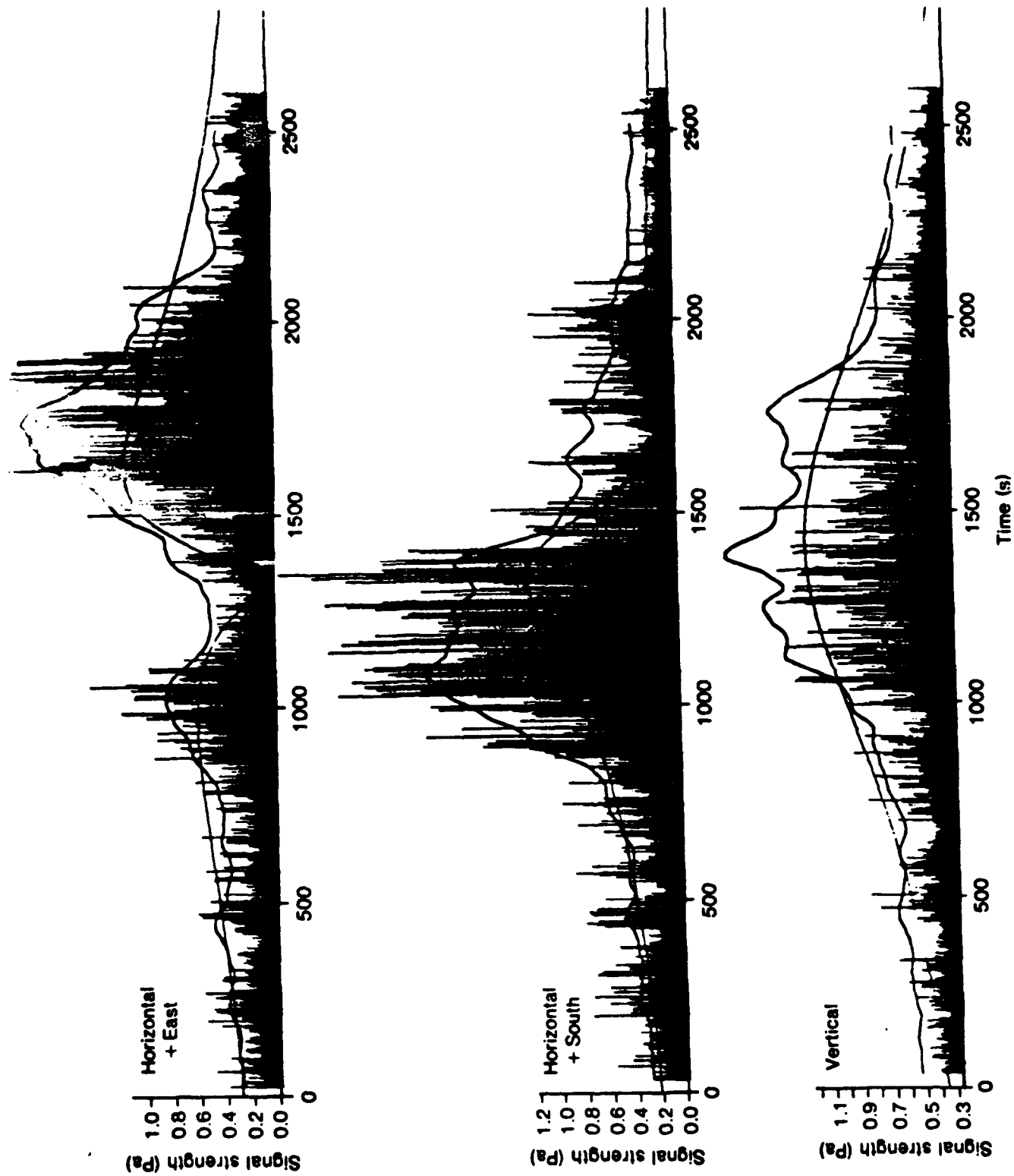


Figure 9

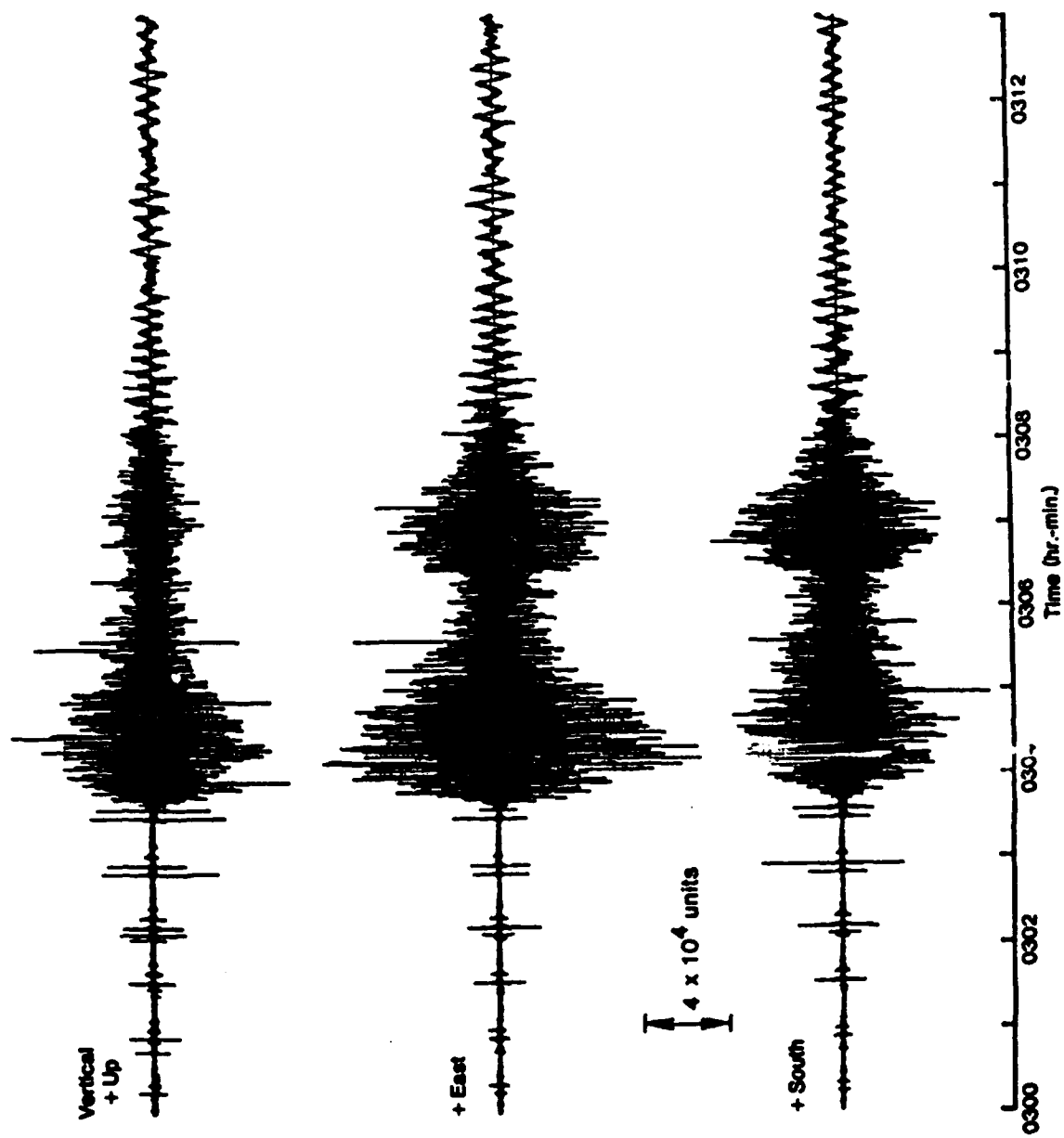


Figure 10

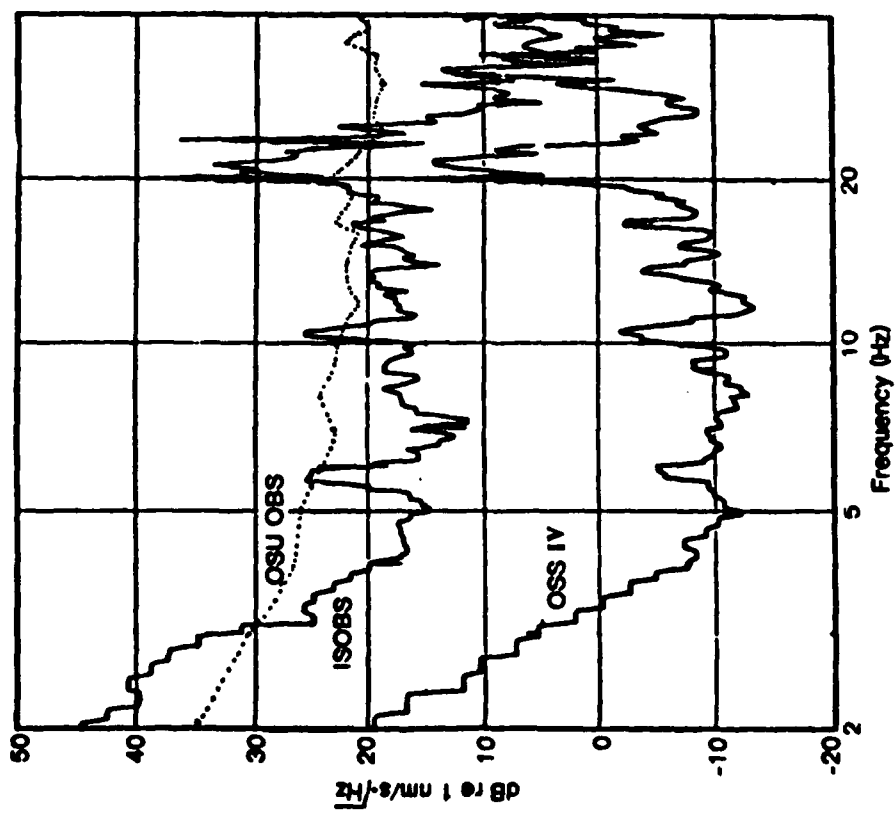
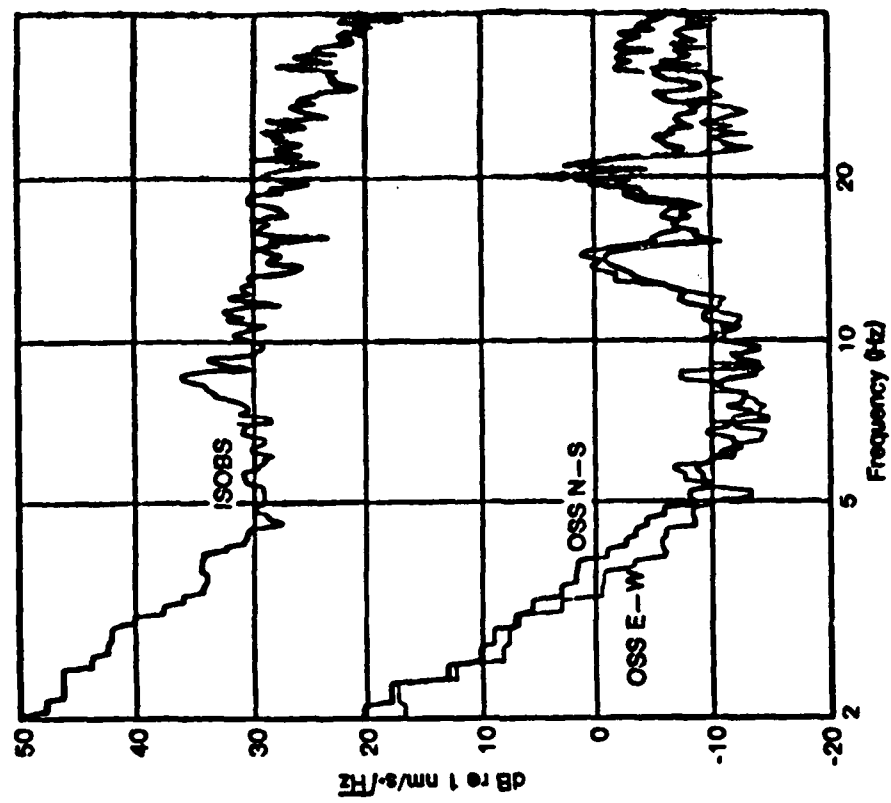


Figure 11

dB re 1 MICROBAR (0.156 Hz BANDWIDTH)
DATA ROTATED COUNTERCLOCKWISE ABOUT 1 Hz BY 18 dB/OCTAVE

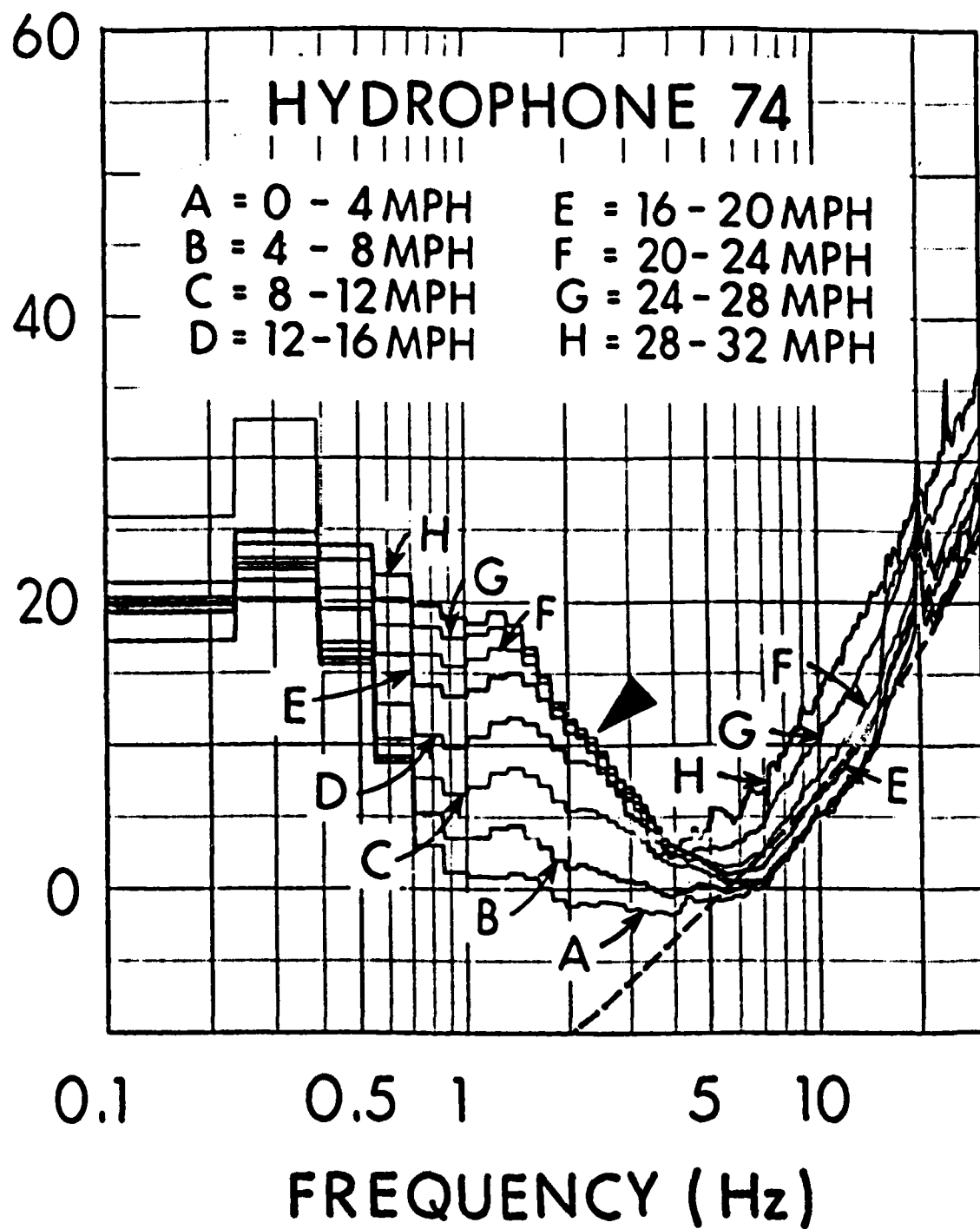


Figure 12

80-YEAR MEAN OCEAN SURFACE WIND SPEED

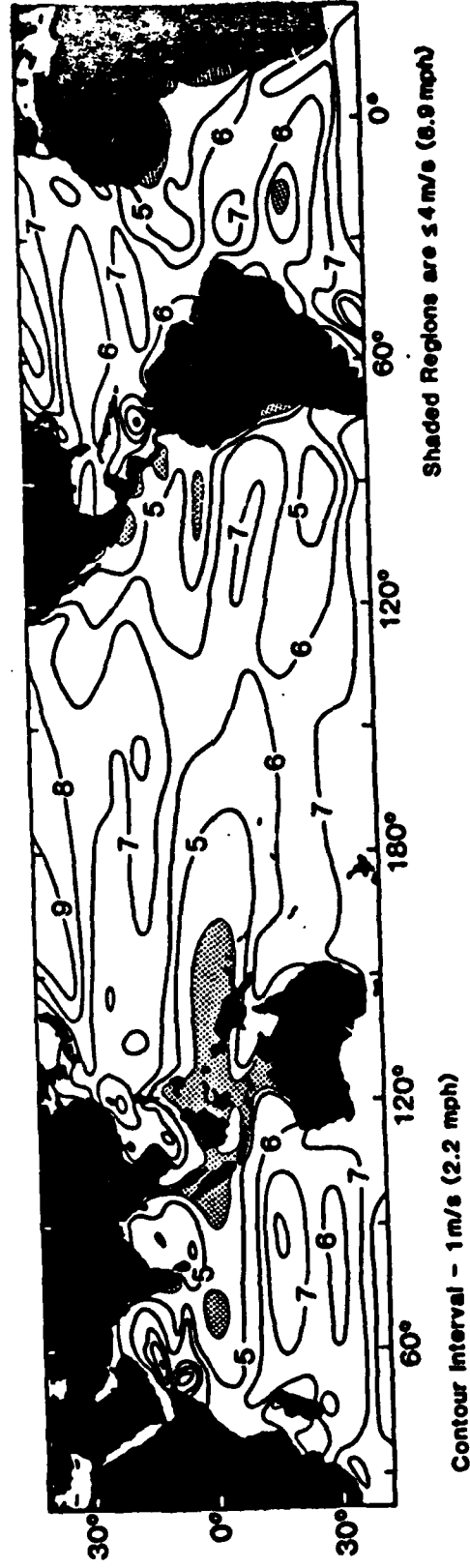


Figure 13

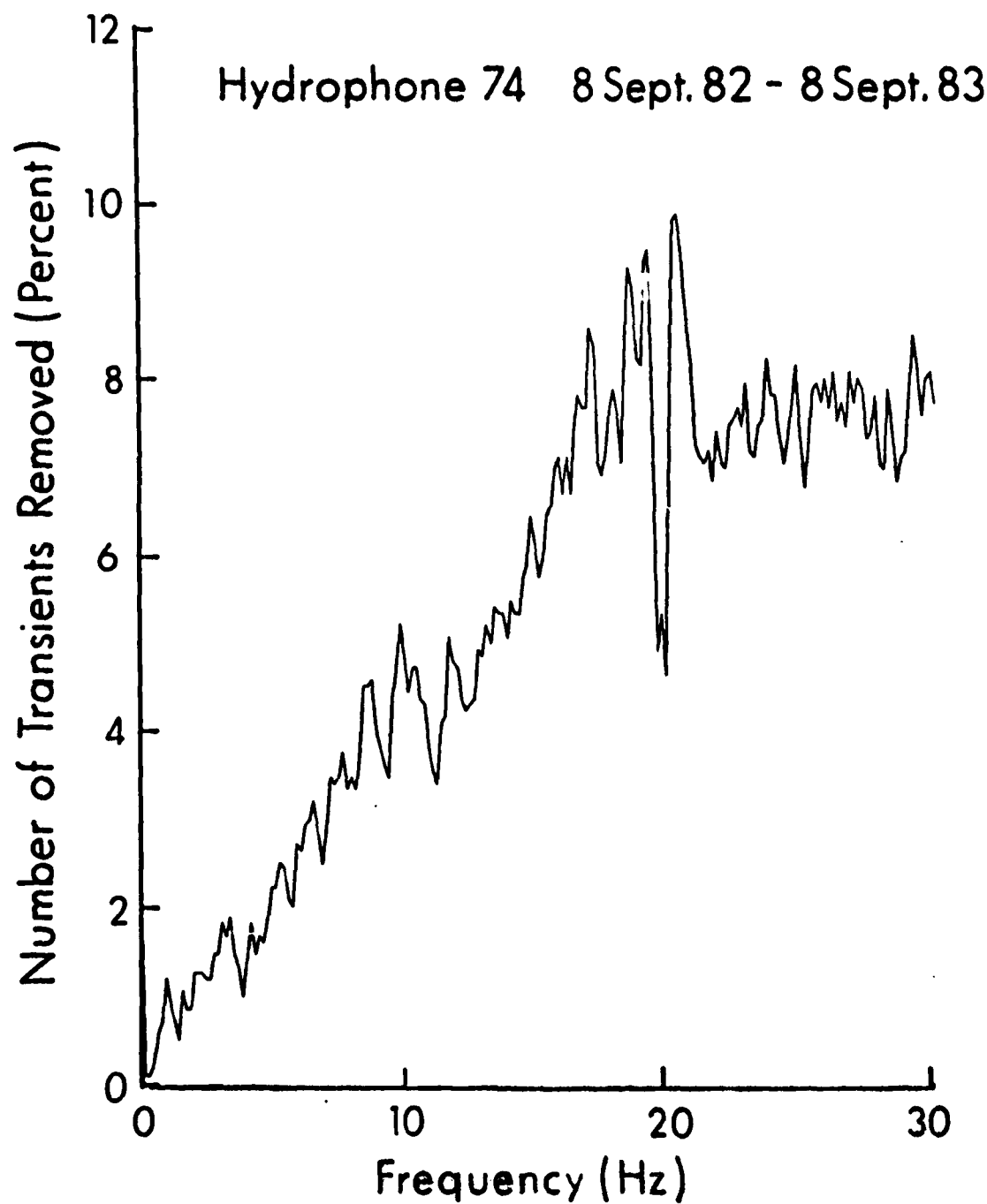


Figure 14

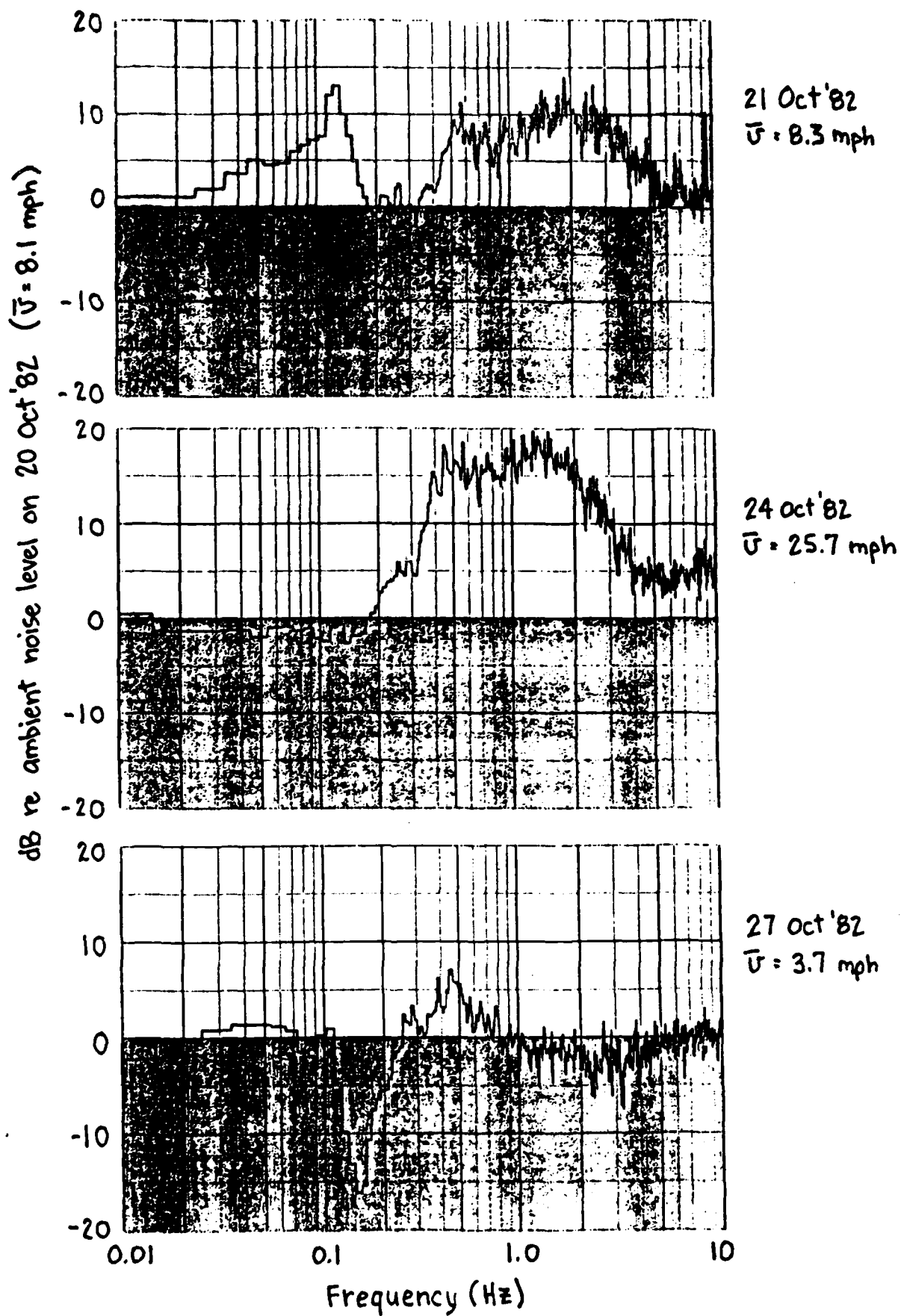
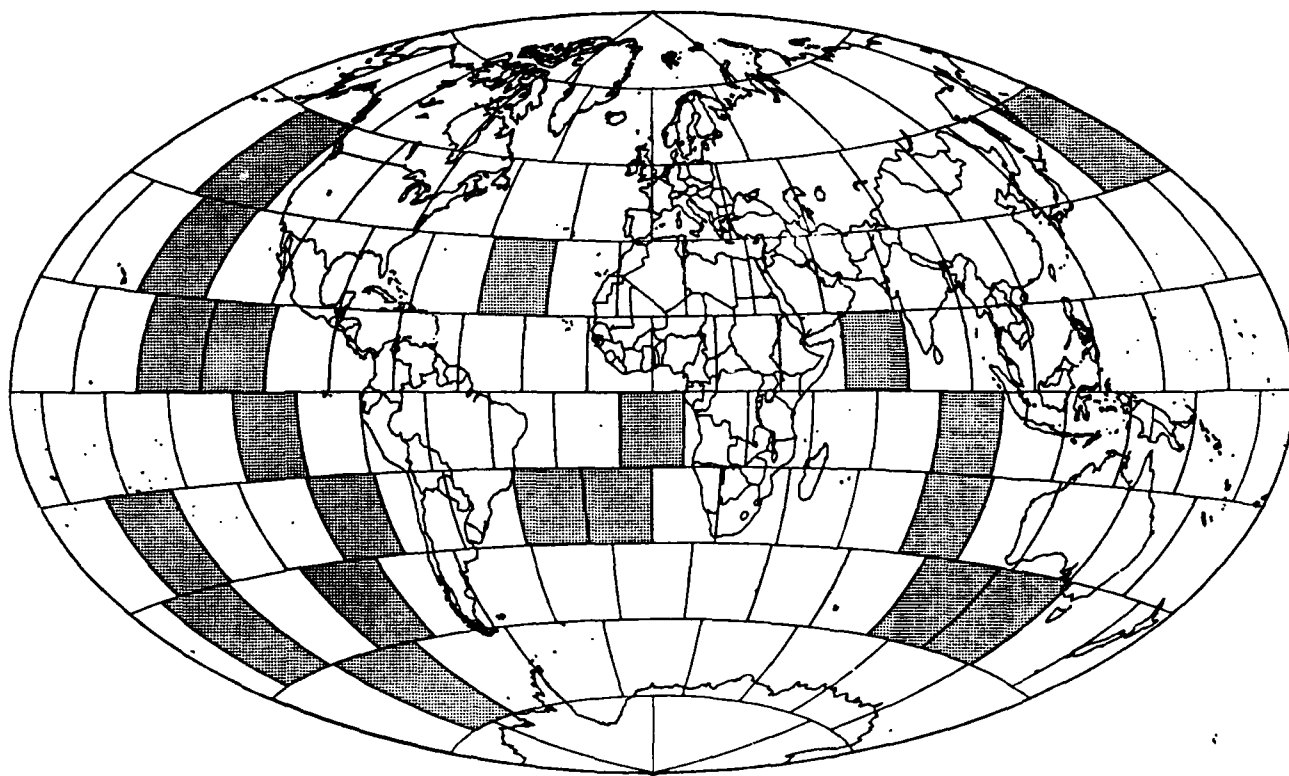


Figure 15

Proceedings of a Workshop on Broad-Band Downhole Seismometers in the Deep Ocean

Woods Hole Oceanographic Institution
Woods Hole, Massachusetts, 02543, USA



April 26-28, 1988

Convenors: G.M. Purdy and Adam M. Dziewonski

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Ocean Floor Seismic (OFS) OBSERVATIONS FOR NUCLEAR DISCRIMINATION RESEARCH

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I. INTRODUCTION

Ocean bottom seismic stations could play an essential role in nuclear discrimination research. This stems from the likelihood that the number and location of ocean bottom stations, located in international waters, will not be subject to regulation. Significantly, the world's most tectonically active areas, where discrimination is most difficult, are near the deep ocean. These areas include the entire Pacific margin (i.e., "the Ring of Fire"), the Alpine-Himalayan tectonic belt extending from the Mediterranean through the Middle East to Indonesia and, of course, the oceanic ridges. In fact, nearly all of this entire area is within 5° of international waters. Even the Himalayan tectonic belt is less than 20° from the ocean. Clearly internal land stations, whose number and location are likely to be restricted by a host nation, are not necessary to study these high seismicity areas. In any event, available land station should not be wasted here. They would be better used to those internal regions whose geologic structure would lend itself to decoupling-type evasion techniques.

The use of ocean bottom stations for regional discrimination research is predicated, of course, on the ability of such stations to detect seismic events as effectively as alternative land stations. Unfortunately, adequate information is not available to assess the relative performance of ocean bottom stations in a near-in, or regional context. Previous experiments sponsored by ARPA in the early 1960's indicated that ocean bottom stations would not be as effective as land stations for global teleseismic surveillance. This judgment was based on the observation that the background noise level, measured at several sites by short period seismometers, was much higher than at land stations. The instruments were deployed by simply dropping them onto the seafloor mud and ooze. Although these instruments were not able to examine the long period noise which earlier workers suggested was comparable to land observations, extrapolation of the short period results suggested that long period noise levels would also be higher than land station levels. Accordingly, the concept of using ocean bottom stations for teleseismic monitoring was abandoned in the late 1960's.

Today such a judgment may no longer be valid in view of recent comparisons of short period S/N ratios of OBS and borehole instruments. It appears that modern digital seismographs rigidly emplaced beneath the seafloor by deep sea drilling ships, manned submersibles, or remote controlled manipulator ships can provide inexpensive ocean bottom stations useful for both long period teleseismic and short period regional monitoring. In fact, by incorporating modern acoustic satellite and seafloor cable data telemetering techniques, it should be possible to have essentially real-time monitoring comparable to land stations.

This report summarizes the role that ocean floor observatories might play in modern discrimination research. Below, we discuss the advantages to using ocean floor stations that have come about from recent advances in ocean technology.

II. ADVANTAGES OF OCEAN BOTTOM STATIONS (OBS's)

A. Ocean floor Observations vs Land Stations

Aside from their obvious political desirability, ocean floor seismic observations may have important scientific and technical advantages over land stations for nuclear discrimination research. Some of these are:

1. Increased Signal Amplitude

Although most previous experiments have probably not provided a faithful portrayal of true ground motion on the seafloor because of poor coupling and high noise, it is clear that signal amplitudes from earthquakes observed on the ocean floor are generally higher than those seen by a land station. For example, the ARPA-sponsored field tests off the Aleutian Islands in 1968 showed that OBS-calculated m_b values averaged 0.2 unit greater than land station calculated values. This was thought to result from the fact that the rays travelled a slightly shorter path to the ocean bottom stations and, more important, they did not have to propagate through a low Q continental crust. Also, more recent work has shown attenuation along oceanic lithosphere paths to be extremely small. Q values are estimated to exceed 6000. For the higher frequency band which will be particularly useful in regional monitoring, this signal enhancement could be significant.

2. Lower Noise

Deep ocean sites far from land would be relatively isolated from the sources of background noise likely to affect seismic stations. These are: cultural noise, breaking surf on coastlines, storm microseisms, and local sea surface waves or tidal current effects. In practice this appears to be the case. Both the early work of Lamont and the later ARPA-sponsored Texas Instruments field tests showed decreased noise with increasing water depth and increasing distance from land. The dominant noise source is believed to be surf microseisms propagating out from the coastline as Rayleigh waves in the water mass and along the water-seafloor interface. The latter path is particularly energetic.

It must be emphasized at this point that, after considering the field method used to make background noise observations, the apparent high noise levels may not have been a true measure of solid-earth motions. In the T.I. system and for that matter with most systems: (i) the seismometers simply rested on surficial, unconsolidated seafloor sediments and ooze whose seismo-acoustic properties were not much different than the overlying water mass; OBS position 1), and (ii) most systems used tall vertical frames which protruded into the water mass to house their seismometers. These facts suggest that such devices probably recorded ocean water as well as solid-earth ground motion. Significantly, those seafloor instruments with seismometers well coupled to the solid earth and isolated from the "wind-like" fluid motions induced on the housing frame by ocean currents and turbulence as well as the tilt of soft sediment have shown short period noise levels approaching the 1-10 $m\mu$ levels observed at the better land SRO stations. These include the early Lamont devices of the 1950's ($\approx 1m\mu$) and the more recent Japanese and British OBS's ($\approx 25-50m\mu$). Notably, most OBS devices have been plagued by much higher noise levels. In fact, some show strong frame-sediment resonance.

Unfortunately, no recent studies of long period seafloor noise have been made. In fact, only the two long period OBS's developed at Lamont in the early 1960's have had significant recording durations. One of these, a shore cable connected system off California, operated from the mid-1960's until the mid-1970's. Unfortunately no definitive analysis of noise observations from this device has been reported. However, information from a short duration recording (8.5 days) off Bermuda show noise amplitudes about 2

orders of magnitude greater than today's typical land SRO stations (i.e., 5 μ vs 50 m μ). Again, these measurements are subject to the same doubts expressed about the short period observations in that these devices were essentially free-fall instruments resting on the sediment surface of the seafloor.

In summary it appears that the better free-fall OBS's existing today have short period noise levels approaching land stations. These low noise levels combined with the expected higher signal amplitude on the ocean floor suggest that even these simple seafloor-type, pop-up OBS instruments have a S/N ratio useful for regional discrimination research. With their improved coupling of borehole seismometers to the solid earth and their isolation from water motions and resonance effects, it is probable that ocean-floor borehole seismic observatories may have long and short period S/N ratios higher than island and OBS stations could be developed for both teleseismic and regional discrimination research.

3. More Uniform Crust and Mantle Structure

The crust and mantle structure beneath the ocean basins is now known to be much simpler than that beneath the continents. The seafloor spreading hypothesis, generally accepted by ocean scientists to account for the formation of the seafloor, predicts that nearly horizontal subplanar rock layers underlie most of the deep ocean. Only at mid-ocean ridges, deep trenches, and oceanic islands will there be significant lateral inhomogeneity of earth structure. Deep sea drilling, seismic refraction, and gravity and magnetic measurements support this hypothesis.

Such simple layering implies that large aperture arrays could be deployed to further improve the S/N ratio by beamforming or velocity filtering. In fact, many of the signal processing problems caused by the near-field complexity of earth structure at land large aperture arrays (e.g., LASA, NORSAR) should not be encountered. By sharply reducing signal-generated coherent noise, a closer approach to the ideal \sqrt{N} signal to noise ratio improvement might be realized. The widespread uniformity of earth structure beneath the deep ocean basins also implies that much larger arrays than those practical for land installation could be built.

4. Simplified Operation

The operational advantage of remote OBS stations may be significant since no on-site personnel are involved. Also, by employing acoustic and buoy/satellite data telemetering techniques, ship costs for data retrieval or costs for interconnecting cables or satellite telemetry necessary for real-time data links are eliminated. In fact, deep sound channel (SOFAR) hydro-phones like the Air Force's Missile Impact Locating Systems (MILS) could provide a reliable quasi-real time monitoring capability on a global scale. Of course, moored satellite telemetering buoys with only local short range acoustic links to the ocean floor observatories or a completely hard-wired cable system could be used. Unfortunately, these real-time monitoring approaches would probably make ocean floor observatories cost more comparable to land internal stations.

5. Greater Geographic Coverage

Since oceans occupy 70% of the earth's surface and many areas have no islands suitable for seismic observatories, it is difficult to infer the seismic structure beneath the ocean basin areas using only land stations. In any event, observations made from island stations are likely to be unrepresentative of the broad ocean crust and mantle structure. A well distributed network of ocean bottom seismographs and/or large aperture arrays would fill this gap in our knowledge. Also, the low level seismicity of such important features as trenches and mid-oceanic ridges which are only accessible with ocean floor observatories can be examined. These observations could have important ramifications for general earthquake research as well as for nuclear discrimination research.

B. Borehole Seismometers vs Seafloor OBS's

The most effective method to improve both the signal noise ratio and discrimination performance of ocean floor seismic observatories is to rigidly mount the seismometer beneath the soft sediment layer.

1. Better Coupling to the Solid Earth

Competent semi-consolidated sedimentary materials are generally found a few tens of meters beneath the unconsolidated surficial seafloor sediments. These deeper, lithified layers show sharp increases in both compressional and shear wave velocities and bulk density. In fact, the hard, crystalline igneous rocks of the High Q oceanic crust are usually covered by less than a few hundred meters of sedimentary materials in most areas. Accordingly, a borehole-type seismometer installation, much like the present SRO stations, which is employed in the hard sediment or on/within the oceanic basement rocks should provide signal coupling vastly superior to free-fall devices resting on the soft sediment/water interface. Also, the signal amplitude can be maximized by simply adjusting the overall seismometer case density to match the acoustic impedance of the surrounding borehole rock materials.

2. Lower Noise

The depth of burial necessary for the seismometer to attain a significant noise reduction is probably only a few tens of meters due to the sharp gradient in the seismo-acoustic properties of the soft seafloor sediments. A buried seismometer is not only isolated from the wind-like noise induced by the ocean currents and turbulence on the housing frame but the soft overlying surficial material may act much like a soundproofing layer which will absorb ocean-generated noise. In addition, the air-water and seafloor-water interfaces will serve as efficient reflectors which effectively trap any propagating waves within the water volume. Tests conducted by Woods Hole/Miami scientists in shallow water showed more than a factor of ten reduction in local wind/current-generated noise on a vertical component, short period seismometer buried only a few meters beneath the seafloor. Notably, some of the early Lamont OBS's which reported very low noise levels had their seismometers in probe-like legs which penetrated the seafloor a few meters.

The coherent microseism noise propagating as Rayleigh waves in the ocean water and along the seafloor sediment/water interface is also markedly attenuated with increasing depth since the shear wave velocity of the surficial sediments is only about 0.2 km/sec. Thus, the microseism noise which is generated beneath breaking surf on distant beach surfaces does not penetrate very deeply into the soft sediment layer. Seismometers buried 300-600 meters beneath the seafloor would be virtually shielded from this dominant source of seafloor noise.

3. Reduced Signal Contamination

Seismic signals received at a seafloor-type, pop-up OBS travel through the ocean water as well as through the solid earth beneath the station. Those rays arriving at the OBS which are reflected from the local air-sea surface interface, particularly, contaminate the direct seismic arrival phases. This signal-generated noise not only introduces apparent complexity and reverberation in the wave train coda but it also tends to generally reduce signal amplitude because of interference. Accordingly, by locating the seismometer in a borehole beneath the seafloor surface, seismic signals entering the overlying water mass and soft sediments will be effectively trapped much like noise initially generated in the ocean. In fact, seismometers near the oceanic basement-hard sediment interface should be virtually free of reflected arrivals returning from overlying interfaces.

Seismicity of the Interiors of Plates in the Pacific Basin

by

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Abstract. Historical listings of instrumentally recorded earthquakes raise serious questions about the validity and usefulness of the long-held presumption that the interiors of ocean plates are aseismic stable masses. Unusual distributions of epicenters within these regions may indicate stress patterns resulting from plate motions, or may indicate nascent subduction zones, ridge systems, or hot spots.

INTRODUCTION

In an earlier investigation (Walker and McCreery, 1988) data recorded on ocean bottom hydrophones and seismometers revealed twenty-eight intraplate earthquakes in the deep interior of the Northwestern Pacific Basin which were unreported by the worldwide network of land-based seismic stations. The data sources included drum recordings of hydrophones near Wake and Enewetok in operation for various time intervals from 1963 through 1969, tape recordings from a nine-element 1500-km-long linear array of hydrophones in operation for two months in 1981, and tape recordings from September 1982 through 1985 of an eight-element hydrophone array near Wake Island. The number of unreported earthquakes and their large signal strengths at great distances (signal to noise ratios as high as 40/1 were observed at a distance of 2268 km) far exceeded what might be expected based on the long-held presumption that ocean plate interiors were aseismic stable masses. Nonetheless, the presumption of aseismicity in the portion of the Northwestern Pacific Basin examined in Walker and McCreery seemed to be supported by world seismicity maps such as the U.S. Geological Survey's (USGS) "World Seismicity Map" (Tarr, 1974) which has only one earthquake plotted in this region, or the U.S. National Earthquake Information Service's (NEIS) "Global Distribution of Seismicity" (Guter, 1987) which has only three earthquakes in this region.

The apparent conflict between the presumption of aseismicity and the levels and strengths of earthquakes actually observed led to the examination of listings of earthquakes from 1905 through 1983 provided by the International Seismological Centre (ISC) of Berkshire, England and listings from 1905 through 1986 provided by the National Geophysical Data Center (NGDC) of Denver, Colorado.

From these listings twenty-eight reported earthquakes were found in the Northwestern Pacific Basin. Many had locations similar to those of the unreported earthquakes. The ISC data were found to be more comprehensive than the NGDC data. For example, sixteen earthquakes were reported by the ISC from 1964 through 1983, none of which was reported by the NGDC. Many errors were found in both listings when their entries were

checked against primary data sources such as the International Seismological Summary, ISC regional catalogs, U.S. Coast and Geodetic Survey listings, USGS listings of epicenters, and NEIS monthly listings. Problems encountered with data on the ISC and NGDC listings included: missed, added, or incorrect digits on coordinates; °S transcribed as °N; stated poor solutions; multiple solutions, only one of which was in the region of interest; unconfirmed solutions; or solutions recomputed by Gutenberg and Richter (1941) and found to be incorrect. As a result, nearly 50% of the entries on the ISC listing had to be discarded. Problems associated with the NGDC data were greater in number than those associated with the ISC data.

In spite of these difficulties, the ISC data were very important in providing a clearer picture of seismicity for the Northwestern Pacific Basin than had been available from existing seismicity maps. Thus with the ISC data and the data from ocean bottom hydrophones and seismometers, the presumption of aseismicity seemed, at the very least, to be suspect and a possible impediment to a comprehensive understanding of the stress and deformation of ocean plate interiors.

In retrospect, the problem with the seismicity maps already mentioned is that they are too restrictive. The USGS map has earthquakes only for the time period 1 July 1963 through 1972 with magnitudes ≥ 4.5 reported by 10 or more stations. The NEIS map has earthquakes only for the time period 1 January 1977 through 1986. The data sources used for each of these maps were U.S. government agency listings (USGS, NGDC, or NEIS) and excluded the more comprehensive data listings of the ISC. Thus, in using more comprehensive data listings of reported earthquakes and data from ocean bottom hydrophones and seismometers, the picture changes from that of a region with no more than three earthquakes to a region with fifty-six earthquakes. The results of this investigation led to an expansion of the study to the entire Pacific Basin. The results of this expanded study are the topic of this report.

DATA

Since the focus of this study is on the presumed aseismic interiors of Pacific plates, areas known to be seismically active are excluded. These excluded regions consist of subduction zones, ridge systems, and the Hawaiian and Tuamotu islands whose seismicity is attributable directly or indirectly to hot spot activity.

In all of the remaining interior regions (Fig. 1), there appear to be only 14 epicenters on the USGS seismicity map and only 26 on the NEIS map (uncertainty in the numbers results from the possibility of multiple earthquakes with identical, or nearly identical, epicenters). Yet listings of earthquakes for these regions from 1905 through January 1987 provided by the ISC contain 575 events. Of these, 199 were found to be unacceptable for the variety of reasons discussed earlier. Combining the remaining 376 ISC solutions with two exclusively reported by the NGDC for the Northwestern Pacific Basin and the 28 determined from hydrophone and seismometer arrays in the Northwestern Pacific Basin gives the 406 earthquakes shown on the cover of this issue.

Persisting in the notion that the deep interiors of ocean plates are aseismic stable masses, consideration would have to be given to how so many erroneous solutions could have been computed. One possibility is that most of the solutions were substantially in error during the early nineteen hundreds, and that modern, well-determined data would support the presumption of aseismicity for these regions. To examine this explanation, solutions have been replotted in Fig. 2 for three different time periods. Clearly most of the data comes from what would be expected to be the most reliable of these time periods, corresponding to the establishment of the World-Wide Network of Standard Seismographs (WWNSS) in 1964 (Oliver and Murphy, 1971). Since solutions for the older data are often in the same locations as the newer data, substantial errors in early epicenter determinations cannot explain the large numbers of earthquakes observed in these regions. Also, solutions since 1964 based on 10 or more observations (Fig. 3) are distributed throughout the Basin and include some of the most unusual observations (e.g., the seismicity at about 130°W from 12°N to 5°S).

Another independent assessment of seismicity in these interior regions is available through an analysis of T-phase source locations published from December 1964 through 16 January 1967 (Duennebier and Johnson, 1967). In observing high-frequency guided ocean phases, now referred to as Po and So (Walker, 1984), along the east coast of the U.S., Linehan (1940) noticed a third, or tertiary, phase which he called the T-phase (P-primary, S-secondary, and T-tertiary). The T-phase was eventually found to be compressional energy traveling in an acoustical waveguide in the world's oceans (Ewing, Press, and Worzel, 1952) produced primarily by variations in sound velocity with changes in salinity and temperature. The resulting waveguide has been called the SOFAR (sound fixing and ranging) channel. Sound propagation is so efficient in this waveguide that small charges (1.8 lbs of TNT) in the SOFAR channel have been recorded on hydrophones throughout the North Pacific (Spiess et al., 1968; Northrop, 1974).

In the mid-1960's, the T-phase study group at the Hawaii Institute of Geophysics routinely located T-phase source locations using data from 20 hydrophones at seven stations in the North Pacific extending from Enewetok atoll to California. Figure 4 shows the 206 T-phase solutions (open triangles) computed from December 1964 through 16 January 1967 for the interiors of Pacific plates. [For the entire Pacific more than 20,000 T-phase solutions were determined.] Also plotted in Fig. 4 are the 406 solutions (solid circles) shown on the cover of this issue and in Fig. 2. Although 206 T-phase solutions were determined, only 17 earthquakes were reported by the ISC for the same time period and same regions. Thus, T-phase sources determined for only an approximate two-year period display the same general pattern of seismicity for the interiors of Pacific plates as the entire 82-year history of epicentral determinations based on conventional land-based seismic stations.

DISCUSSION

The 406 earthquake epicenters and 206 T-phase source locations are distributed throughout the presumed aseismic interiors of Pacific plates. Many solutions extend several hundred kilometers out into the oceans beyond what are generally considered to be the leading edges of subduction, the most prominent example being the Kuril-Japan subduction zone. There are suggestions of NW to SE patterns of epicenters extending for thousands of kilometers in the Northwestern Pacific Basin and a N to S pattern across the equator at about 130°W . An unusual cluster already discussed in other publications (Sverdrup and Jordan, 1979; Okal et al., 1980) at about 7°S and 148°W is also apparent. Several small clusters appear within the Nazca and Cocos plates, south of New Zealand, near the equator at about 170°E , and near Pohnpei and Kosrae at about 7°N and 160°E . These latter two clusters and other considerations have been examined as possible evidence for a newly forming subduction zone (Kroenke and Walker, 1986). Another interesting pattern is apparent in the T-phase source location maps at about 40°N and 140°W . These data indicate that low level seismic activity, undetected by conventional land-based seismic stations, extends several hundred kilometers out into the ocean along the Mendocino Fracture Zone, well beyond what is generally considered to be its westernmost limit of seismic activity.

FINAL REMARKS

In the early days of seismology an earthquake's importance was directly related to its size and proximity to population centers. This relationship began to change with the realization that earthquakes could be used to better understand the constitution and dynamics of our earth. Comprehensive studies of the hypocenters and source mechanisms of large numbers of even small earthquakes, in such remote and seemingly unimportant regions as mid-ocean ridges and sparsely populated island arcs, were critical elements in the formulation of modern plate tectonic theories (Isacks, Oliver, and Sykes, 1968).

Most of the earthquakes presented in this study are also small and inconsequential in terms of risk to life and property. Although some may be the result of isostatic readjustments, others may provide a more accurate picture of subduction and ridge processes, as well as important clues related to stresses and deformations within ocean plate interiors. In some cases they may be indicative of incipient trenches, ridges, or hot spots. Although the determination of source mechanisms would be most useful in resolving these differing interpretations, the actual number of available solutions is probably quite small. Of the entire 378 reported earthquakes for the interiors of the Pacific Basin, 236 were reported since the installation of the WWNSS in 1964. Of these, only 18 had body wave magnitudes in excess of 5.0, with the largest being a 5.6 and two 5.5's. Nonetheless, 103 of the 236 earthquakes were reported by ten or more stations, so a comprehensive first motion analysis of recordings for these earthquakes could provide a significant number of source mechanisms.

The earth is covered mostly by oceans and much remains to be learned about the seismicity of ocean interiors and their margins. It is also apparent that an efficient means for acquiring this knowledge is through the deployment of ocean-bottom seismometer and SOFAR hydrophone arrays. In the past, seismological data has provided the inspiration for important research to a broad spectrum of scientists in the fields of marine geology and geophysics. To this author, it now appears critically important to acknowledge our limited knowledge of ocean seismicity and to make the commitments in ocean seismology necessary for continuing advancements in marine geology and geophysics.

ACKNOWLEDGMENTS

The author would like to thank the worldwide network of seismic station operators and record readers whose efforts during the 20th century have made this study possible. A special acknowledgment is also appropriate for the critically important work of the International Seismological Centre and the National Earthquake Information Service. Much of the progress in earth sciences can be traced to the long-term data bases provided

by these organizations. Appreciation is also expressed to members of the T-phase study group at HIG (R. Johnson, R. Norris, F. Duennebier, S. Hammond, and J. Sasser) for their determinations in 1965 and 1966 of T-phase source locations throughout the interiors of Pacific plates. The manuscript was reviewed by C. McCreery and S. Nagumo, and edited by Barbara Jones. Graphics were provided by Firmin Oliveira, Nancy Hulbirt, and Brooks Bays. This research was supported by the Air Force Office of Scientific Research under grant 89-0339, the National Science Foundation under grant ____, and the Office of Naval Research. Hawaii Institute of Geophysics contribution ____.

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FIGURE CAPTIONS

Cover. Earthquake epicenters for the interiors of plates in the Pacific Basin from February 1905 through January 1987. Data has been taken from listings of the International Seismological Centre and the National Geophysical Data Center. Also shown are 28 earthquakes determined from recordings of hydrophone and seismometer arrays in the Northwestern Pacific Basin. A total of 406 earthquakes are plotted. Many are located far out into the oceans beyond what are now considered to be the leading edges of subduction. Others display intriguing patterns in various locations throughout the Pacific. For additional details and independent confirmation of this seismicity using 206 T-phase source locations see the article, *Seismicity of the Interiors of Plates in the Pacific Basin*, by D.A. Walker, p. _____. Poster sized copies of this seismicity map are available from the author.

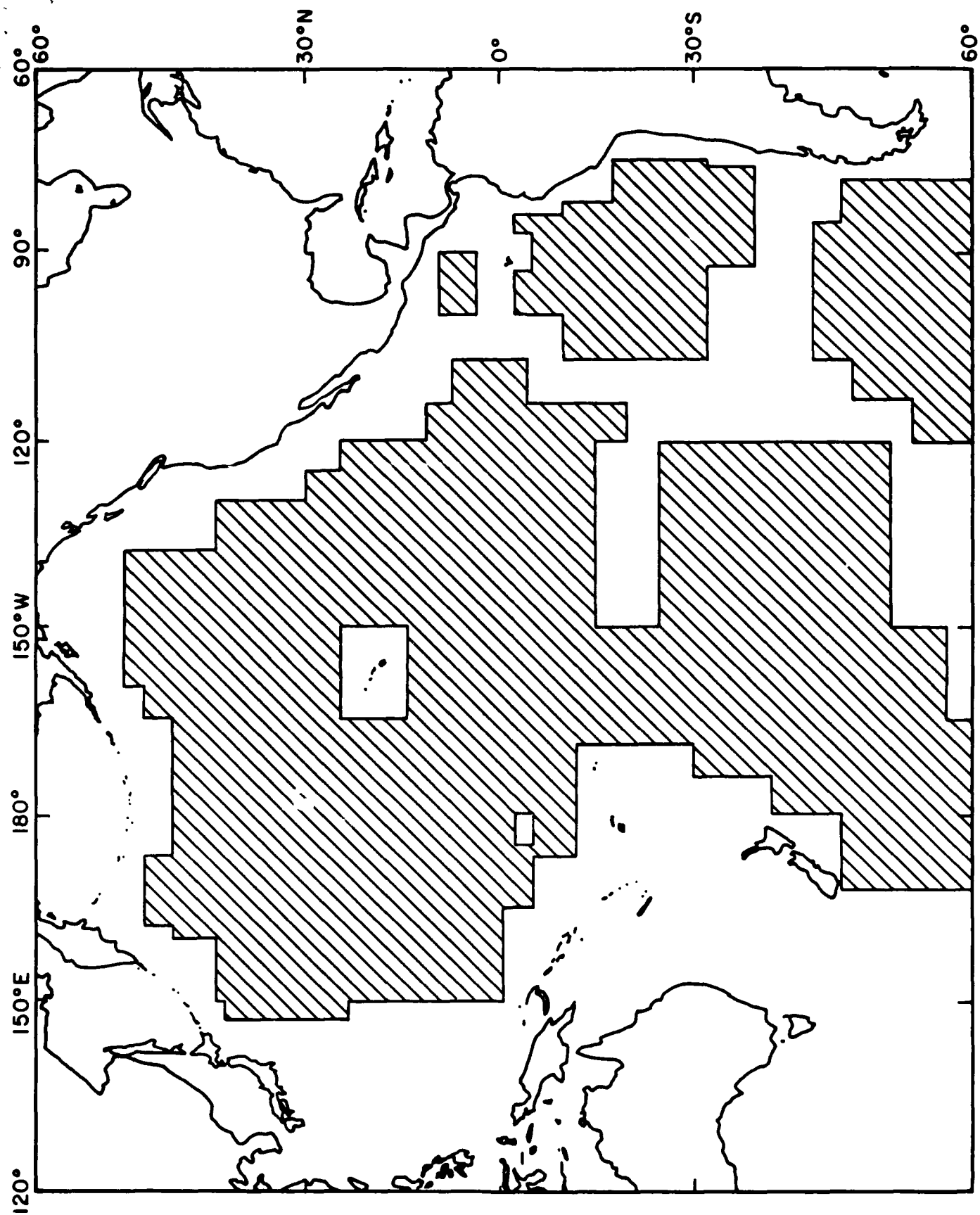
Fig. 1. Portions of the interiors of Pacific plates investigated in this study (hatched regions).

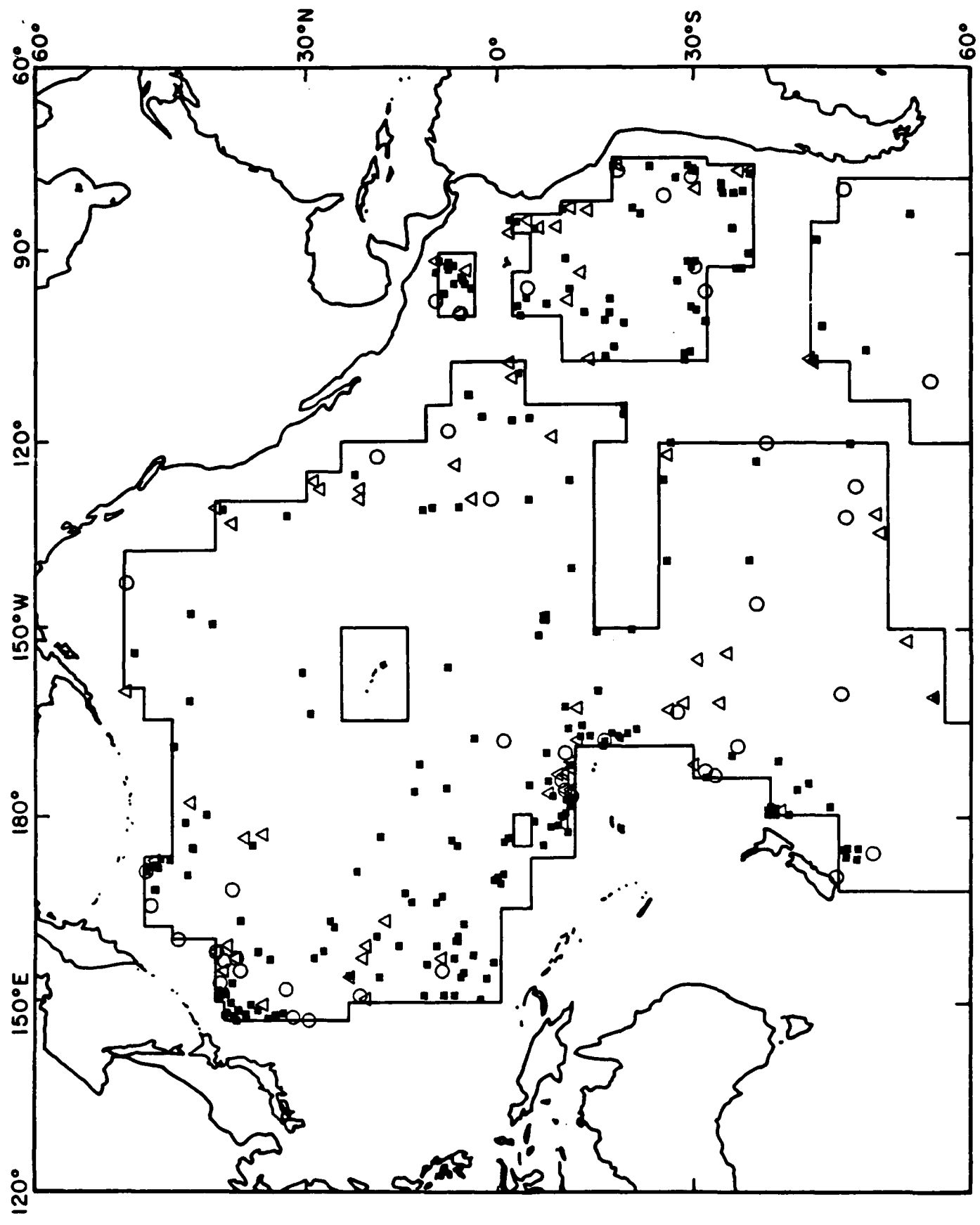
Fig. 2. Earthquake epicenters in the interiors of plates in the Pacific Basin. Open circles indicate solutions for the years 1905 through 1929, open triangles for 1930 through 1963, and solid squares for 1964 through January 1987.

Fig. 3. Earthquake epicenters determined by ten or more stations from 1964 through January 1987.

Fig. 4. T-phase source locations from December 1964 through 16 January 1967 (open triangles) and earthquake epicenters from February 1905 through January 1987 (solid circles) for the interiors of Pacific plates.

Fig. 1





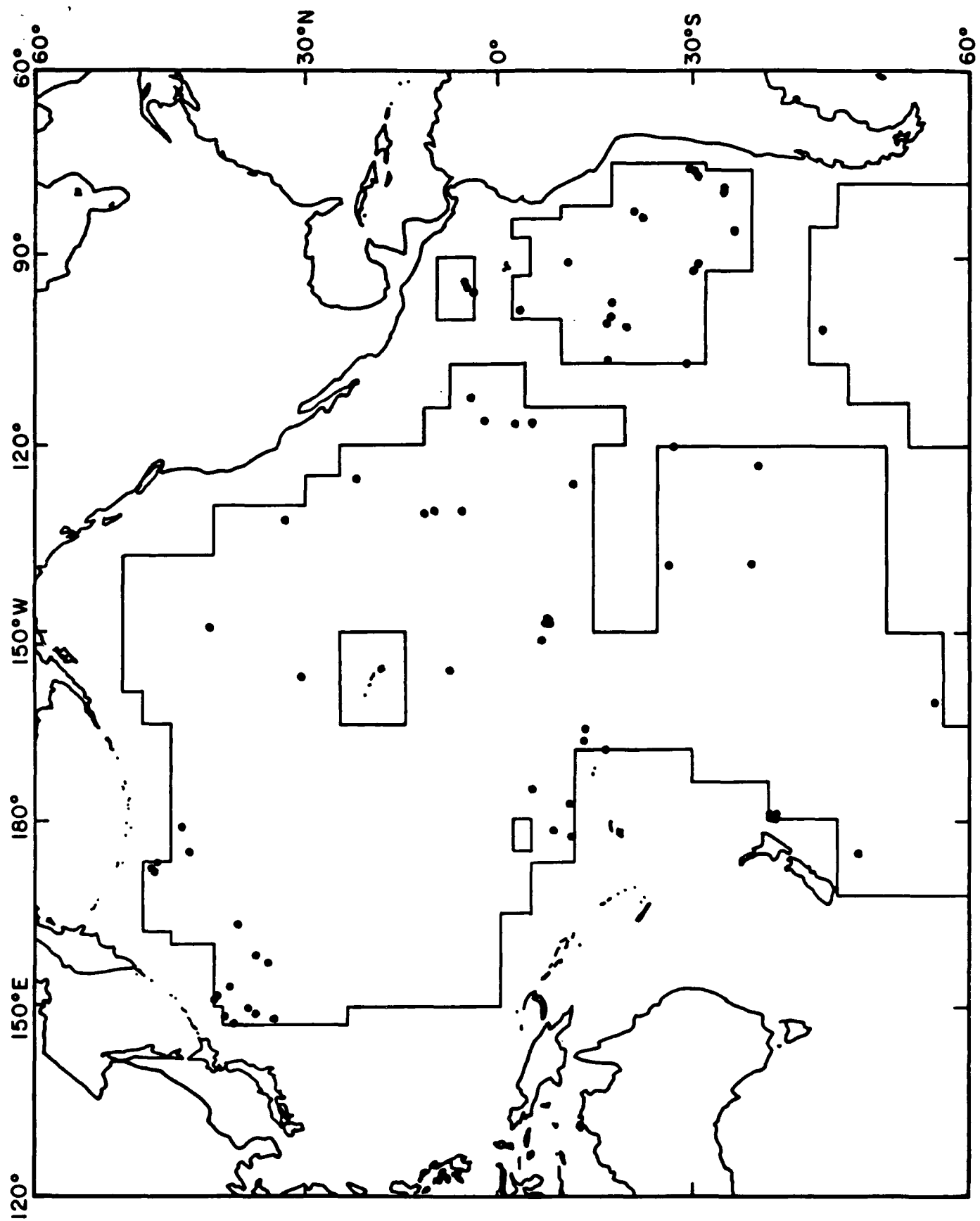
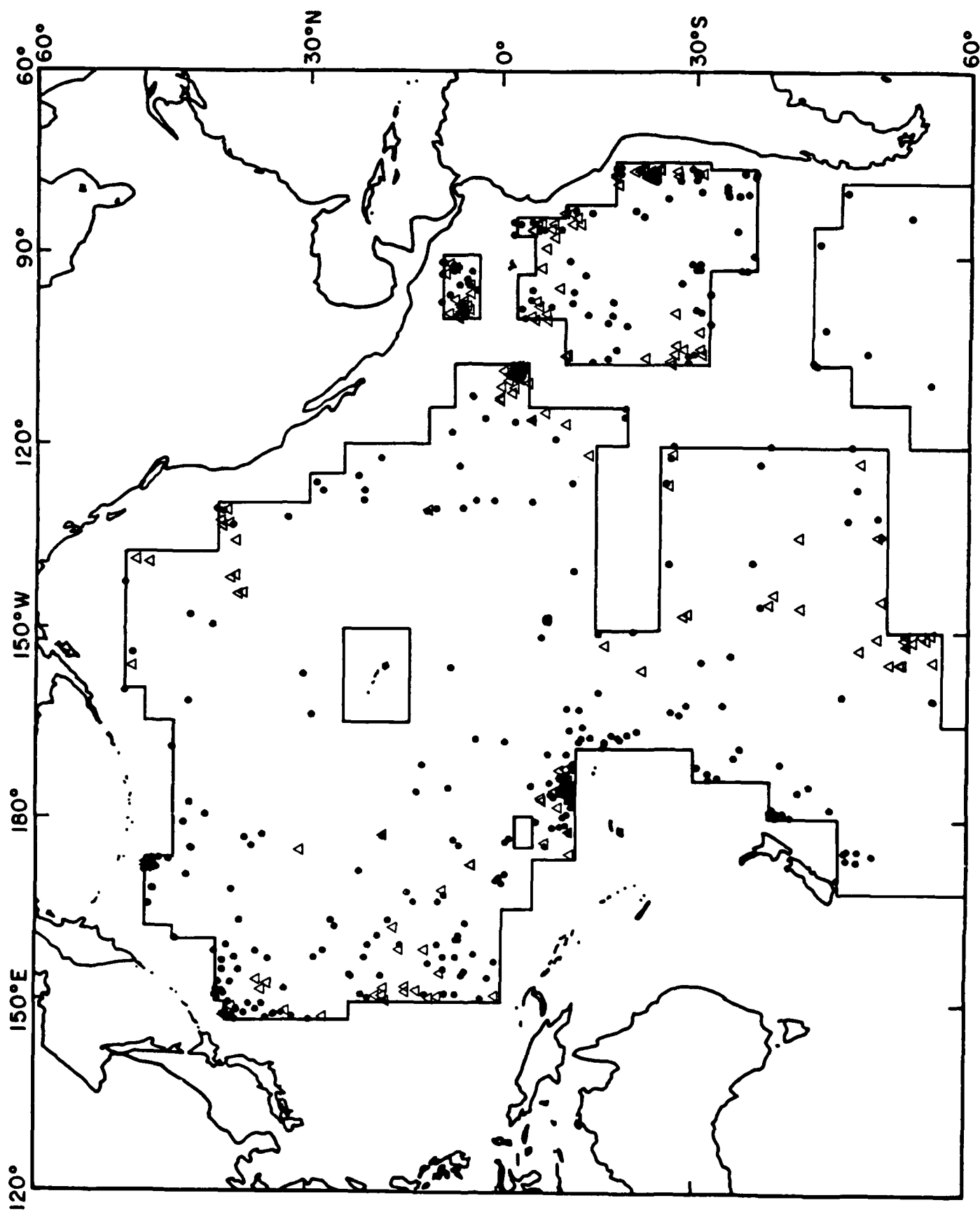


Fig. 4



EOS

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Cover. The map on the cover shows the existing worldwide network of coaxial trans-oceanic telecommunications cables which are being complemented by a new generation of fiber optic cables. Because of the greater channel capacity of fiber optic cable, most of the existing coaxial cables will be retired from commercial use, thereby providing the community of earth scientists with a unique opportunity for deploying a variety of geophysical instruments throughout the world's oceans. Actual testing of the re-use of trans-oceanic cables for geophysical observatories could begin as early as 1989. This diagram of cable routes is after "Global Network System" (plate), Kokusai Denshin Denwa, Ltd./1987 (Ann. Rept.), Kokusai Denshin Denwa, Ltd., Tokyo, p. 22-23 and after "Coaxial Submarine Cables and Cable Ships in the Pacific Area," (plate), The Cable Ship KDD Maru, Kokusai Cable Ship Co., Ltd., Tokyo, (inside back cover). For further information see the article, *Re-Use of Trans-Oceanic Telecommunications Cables for Ocean Bottom Geoscience Observatories*, by S. Nagumo and D. Walker, p. _____.

Ocean Bottom Geoscience Observatories

Reuse of Transoceanic Telecommunications Cables

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Global Broadband Seismological Networks: The Ocean Dilemma

One of the most promising areas of international co-operative research in geophysics is broadband seismology. At a recent symposium on this topic (International Symposium on Global Seismology and the POSEIDON Project; University of Tokyo; August, 1988) papers were presented by representatives of the United States, Japan, Russia, the Republic of China, Italy, Germany, Canada, the Netherlands, and Australia. National and international associations of earth scientists committed to the establishment of a global network of broadband instruments include: the USGS; POSEIDON (Pacific Orient Seismic Digital Observation Network) of Japan; IRIS (Incorporated Research Institutions for Seismology) of the U.S.; GEOSCOPE of France; MEDNET (Mediterranean Network) of Rome and Geneva, but comprising many Mediterranean countries; ORFEUS (Observatories and Research Facilities for European Seismology), a working group of the European Geophysical Society; and CANDIS (the Canadian Digital Seismic Network). An umbrella organization for all of these associations is the international FDSN (Federation of Digital Seismographic Networks).

Broadband instruments might best be defined as those capable of recording all of the seismic waves generated by an earthquake or underground explosion. Typical specifications would include a dynamic range of about 140 dB and a frequency band from about 20 Hz to 10^{-6} Hz. Although many broadband stations are planned (e.g, the USGS plans a network of 150 for the U.S., and POSEIDON plans 50 for East Asia and the Western Pacific), only a handful are now in operation.

Interest in broadband seismology is a result of the wide range of geophysical problems

which could be investigated with data that comprehensively replicates motions actually present at the recording site. These include more precise studies of source mechanisms and earth structure. Regarding source mechanisms, broadband seismograms have been used to better understand the process of faulting and to indicate heterogeneities in the strength of fault zones (Choy and Boatwright, 1981; Kanamori and Astiz, 1985; Houston and Kanamori, 1986; Kanamori, 1986; Astiz et al., 1987; and Choy and Kind, 1987). Such findings have important implications for understanding regional or global tectonics, and, in terms of hazard mitigations, for the estimation of ground motions and the assessment of earthquake risks in various regions. Studies of other source mechanisms which have benefited, or could benefit, from broadband data include those of underground explosions, volcanic eruptions, landslides, and magmatic injections (Aki, 1984; Hasegawa and Kanamori, 1987; Kanamori et al., 1984; Wallace, et al., 1985; Burger, 1986; Kanamori et al., 1986; McCreery, 1987; and McEvilly and Johnson, 1988). Regarding earth structure, the so-called "seismic tomography", which has received extensive coverage in technical journals (Lay and Helmberger, 1983; Anderson, 1984; Dziewonski, 1984; Woodhouse and Dziewonski, 1984; and Garnero et al., 1988) and in the popular press (Anderson and Dziewonski, 1984; and Dziewonski and Anderson, 1984) promises detailed mapping of mantle flow patterns, mantle slab penetration, and the topography of the core-mantle boundary by measuring seismic velocities, anisotropy, and anelasticity throughout the earth. Thus, future research in global seismology can be viewed as a new era for plate tectonics through the imaging of the internal constitution and dynamic motions of the whole earth.

Major barriers to the realization of an effective global network of broadband seismographs are the world's oceans which cover an estimated 70% of the earth's surface. For comprehensive studies of source mechanisms and earth structure, broadband instruments will have to be widely distributed throughout the world's oceans. Such a requirement poses formidable technological and financial difficulties. Systems under consideration by

the POSEIDON group include: (a) modified pop-up ocean bottom seismometer (OBS) systems; (2) OBS systems connected to a buoy with satellite transmission of the data; and (3) OBS systems connected to trans-oceanic, fiber optic cables. At present, prohibitive costs as well as substantial technical difficulties are associated with all of these systems. Islands, of course, could be instrumented with little difficulty, but their distribution throughout the world's oceans is insufficient to meet the requirements of an effective global network. At a workshop on "Downhole Seismometers in the Deep Ocean" (Woods Hole Oceanographic Institution, April 1988), continental as well as ocean seismologists – both theoreticians and technicians – met together for the first time to discuss instrumenting the world's oceans for global seismology. In this report we present a partial solution to the "ocean dilemma" discussed at that meeting.

Re-Use of Retired Cables As Geoscience Stations

Late in 1988, AT&T and KDD (Japan's international telecommunications company) will complete the laying of a new fiber optic cable from Japan and Guam to the U.S. by way of Hawaii (Kobayashi, 1987). The section connecting Japan, Guam, and Hawaii is called TPC-3 (Trans-Pacific Cable No. 3), and the section connecting Hawaii to the west coast is called HAW-4 (Hawaiian Cable No. 4). Since the present cable (TPC-1) connecting Japan and the U.S. has only 138 channels and TPC-3 has 7560 channels, TPC-1 is to be retired from commercial use. Many other new fiber optic trans-oceanic cables are either under construction or are planned. These include: GPT between Guam, the Philippines, and Taiwan to be completed in 1989; HJK between Hong Kong, Japan, and Korea (1990); TASMAN-2 between Australia and New Zealand (1991); Pac Rim East between Hawaii and New Zealand (1993); and Pac Rim West between Guam and Australia (1996). A cable connecting Japan directly to the U.S. mainland (TPC-4) is also being planned. In the Atlantic, TAT-8 (Trans-Atlantic Cable No. 8) should be completed this year, and the completion of TAT-9 is planned for 1991.

As more of the new trans-oceanic telecommunications cables are put into service, many cables now in use will be retired. In the near future, the retirements of TPC-1, GP-1, HAW-1, and COMPAC (Fig. 1) could provide a unique opportunity for the establishment of a trans-Pacific geoscience cable system. Instruments could also be connected to retired cables in the Atlantic. In addition to broadband seismometers, other instruments could include meters to measure gravity, tsunamis, earth tides, deep ocean currents, and electromagnetic fields.

Feasibility Tests Using the Japan-Guam Segment of TPC-1

For a number of years, Japanese seismologists have been discussing the use of oceanic telecommunications cables with officials of KDD. Recent discussions also have been undertaken by U.S. and Japanese seismologists with officials of AT&T. As a result of these efforts, the re-use of the Japan-Guam segment of TPC-1 has been positively discussed by KDD and AT&T. Thus, the first step in fulfilling the dream of a trans-Pacific geoscience cable system may soon become a reality. Instrumenting the Japan-Guam segment will provide a unique opportunity to test the feasibility of such a system. In the discussions that follow, some special problems associated with re-use are presented.

Residual Life

Although the idea of re-use is easily understood and widely accepted, some serious questions concern the estimated residual life of the retired cables. Major factors affecting the life of the system are failures of electronic tubes used in the repeaters and failures of the cable line due to natural as well as artificial disasters. These types of failures have been investigated with KDD and NOEL (NEC Ocean Engineering, Ltd. of Japan's Nippon Electric Company) by use of papers and reports of the original design and manufacture of the cables, as well as data and records of actual performance of the system for more than 20 years.

Two types of tube failures could be expected: the break down of various tube components and the eventual "wear-out" of thermionic emissions. Regarding "break down", the tubes were manufactured so as to satisfy the requirement of a mean time between failures of 885 years (Holdaway, et al., 1964). The estimated number of failures along the Japan-Guam segment in a thirty-five year period due to "breakdown" is 1.0. Design and manufacturing data for thermionic emissions indicate that the theoretical life is more than 50 years (Kern, H., 1960).

In view of these estimates, it is not surprising that most cable failures have been associated with the cables themselves. Occurrence of such failures, however, is rare, most being associated with natural or artificial disasters in shallow-water areas. Therefore, the available supply of spare materials, including repeaters and cables, should permit transmission for many years to come. On the deep sea floor, the cable itself is very stable and keeps its high quality for long periods of time - HAW-1, which has been in operation for more than 30 years, is a good example.

Adjustments of Power and Data Transmission

The installation of sensors into the present cable will require an adjustment of the power feed. The current throughout the cable is a constant 370 mA, and all repeaters are connected in series. The supply voltage will have to be increased according to the demands of the added sensors so as to maintain the required 370 mA current. The voltage drop across each repeater is 45 V, and the present supply voltage to the Japan-Guam cable is 4500 V.

To meet the wide dynamic range requirements of broadband seismic data, the existing cable transmission format will have to be modified from analog to digital. More specifically, the existing FDM-AM (Frequency Division Multiplex - Amplitude Modulation) system will have to be changed to an FDM - PCM (Pulse Code Modulation) system. These analog to digital conversions will take place at the sensor unit. The transmission

capacity of one voice channel will be 7200 Baud, which is appropriate for one sensor unit containing three-component seismometers with sampling rates of 100 Hz.

Sensor Units

Two types of sensor packages are planned: Unit A and Unit B. Unit A will be a three-component seismometer with a shape similar to that of the repeaters used in the existing system. The unit will be installed in the same way that cable defects are repaired, and will be installed mid-way between repeaters so as to minimize the possibility of disturbing the repeaters (Fig. 2). Given the present state of OBS development, the requirements of Unit A for small size and ruggedness prevent it from fulfilling all of the requirements of a broadband system. The instruments now being considered for Unit A are small-size, high-sensitivity accelerometers with flat displacement responses up to 30 seconds. The accelerometers resolving power of about 10^{-7} G corresponds to 1 μm of displacement at a period of about 12.5 seconds. Such sensitivity should be adequate for body wave tomography. In addition, these instruments will, of course, be capable of recording all types of body phases and many surface waves.

Unit B will serve a variety of purposes (Fig. 3). It could contain a gravimeter, magnetometer, electro-potentiometer, pressure sensor, and current meter. It also could be the desired broadband seismometer, or possibly, an ODP (Ocean Drilling Program) downhole seismometer. Because of the large size and weight of this sensor, it could not be installed in the same manner as Unit A. Instead, the deployment of Unit B must utilize a "branching technique" which will require the unit to be attached to one end of a special branching cable which would then be connected to the main cable by a special device called a "branching unit". Since Unit B could contain several sensor elements (some exposed to seawater), special safety devices will be installed to prevent malfunctions of any sensor component from affecting the performance of other components, or the whole system.

Final Remarks

The anticipated retirement of trans-oceanic telecommunications cables in the Atlantic and Pacific will provide unique opportunities for the community of earth scientists to establish much-needed deep-ocean science observatories. An especially important re-use of these cables would be the establishment of deep-ocean broadband seismographs. Such instruments are especially useful for regional and worldwide studies of earth structure using seismic tomography. Some of the topics which can be investigated include mantle flow patterns, mantle slab penetrations, and the topography of the mantle-core interface. Broadband instruments are also especially useful for comprehensive studies of earthquake source mechanisms and seismic risk assessment.

Furthermore, the possible re-use of telecommunications cables has added significance at this time because of: (1) the small number of broadband instruments now in existence; (2) the many national and international associations of earth scientists dedicated to the establishment of a worldwide network of broadband seismographs; and, (3) the special difficulties posed by the world's oceans to the establishment of a useful global network.

The re-use of telecommunications cables should not be limited only to broadband seismology but should also include other seismic instrumentation such as conventional short period seismometers or ODP downhole seismometers, as well as sensors for measuring gravity, tsunamis, earth tides, deep ocean currents, and electromagnetic fields.

Further impetus for ocean seismographs is provided by the discovery of significant unreported earthquakes in the interior of the northwestern Pacific Basin using the high-frequency guided oceanic phases P_o and S_o and by the implication from these studies that ocean basins may be more seismically active than is generally believed (Walker and McCreery, 1988).

Most importantly, we hope to rigorously test the feasibility of utilizing trans-oceanic telecommunications cables beginning in 1989 with the establishment of geophysical observatories along the Japan to Guam segment of TPC-1.

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Figure Captions

Cover. The map on the cover shows the existing worldwide network of coaxial trans-oceanic telecommunications cables which are being complemented by a new generation of fiber optic cables. Because of the greater channel capacity of fiber optic cable, most of the existing coaxial cables will be retired from commercial use, thereby providing the community of earth scientists with a unique opportunity for deploying a variety of geophysical instruments throughout the world's oceans. Actual testing of the re-use of trans-oceanic cables for geophysical observatories could begin as early as 1989. This diagram of cable routes is after "Global Network System" (plate), Kokusai Denshin Denwa, Ltd./1987 (Ann. Rept.), Kokusai Denshin Denwa, Ltd., Tokyo, p. 22-23 and after "Coaxial Submarine Cables and Cable Ships in the Pacific Area, " (plate), The Cable Ship KDD Maru, Kokusai Cable Ship Co., Ltd., Tokyo, (inside back cover). For further information see the article, *Re-Use of Trans-Oceanic Telecommunications Cables for Ocean Bottom Geoscience Observatories*, by S. Nagumo and D. Walker, p. _____.

Figure 1. Map showing the location of coaxial trans-Pacific telecommunications cables which may be retired from commercial use in the near future (after Kobayashi, 1987).

Figure 2. Schematic diagram showing sensor unit A (a small three component seismometer) installed between two repeaters.

Figure 3. (a) Schematic diagram showing sensor unit B (broadband seismometer, gravimeter, magnetometer, electro-potentiometer, pressure sensor, and/or current meter) connected to the end of a special branching cable which is connected to the main cable with a special branching unit located midway between repeaters. (b) Unit B could also be an Ocean Drilling Program downhole seismometer.

Fig. 1

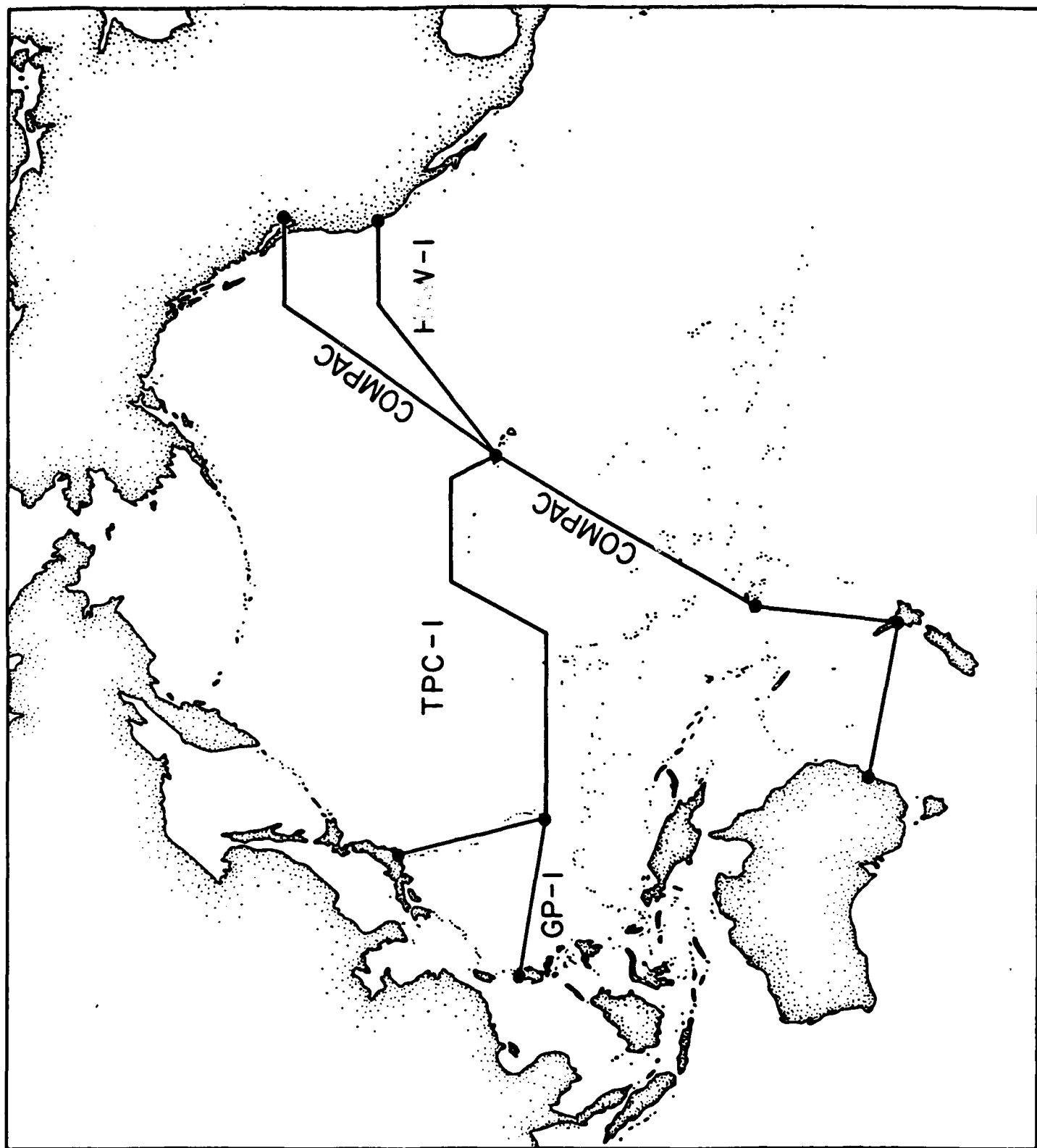


Fig. 2

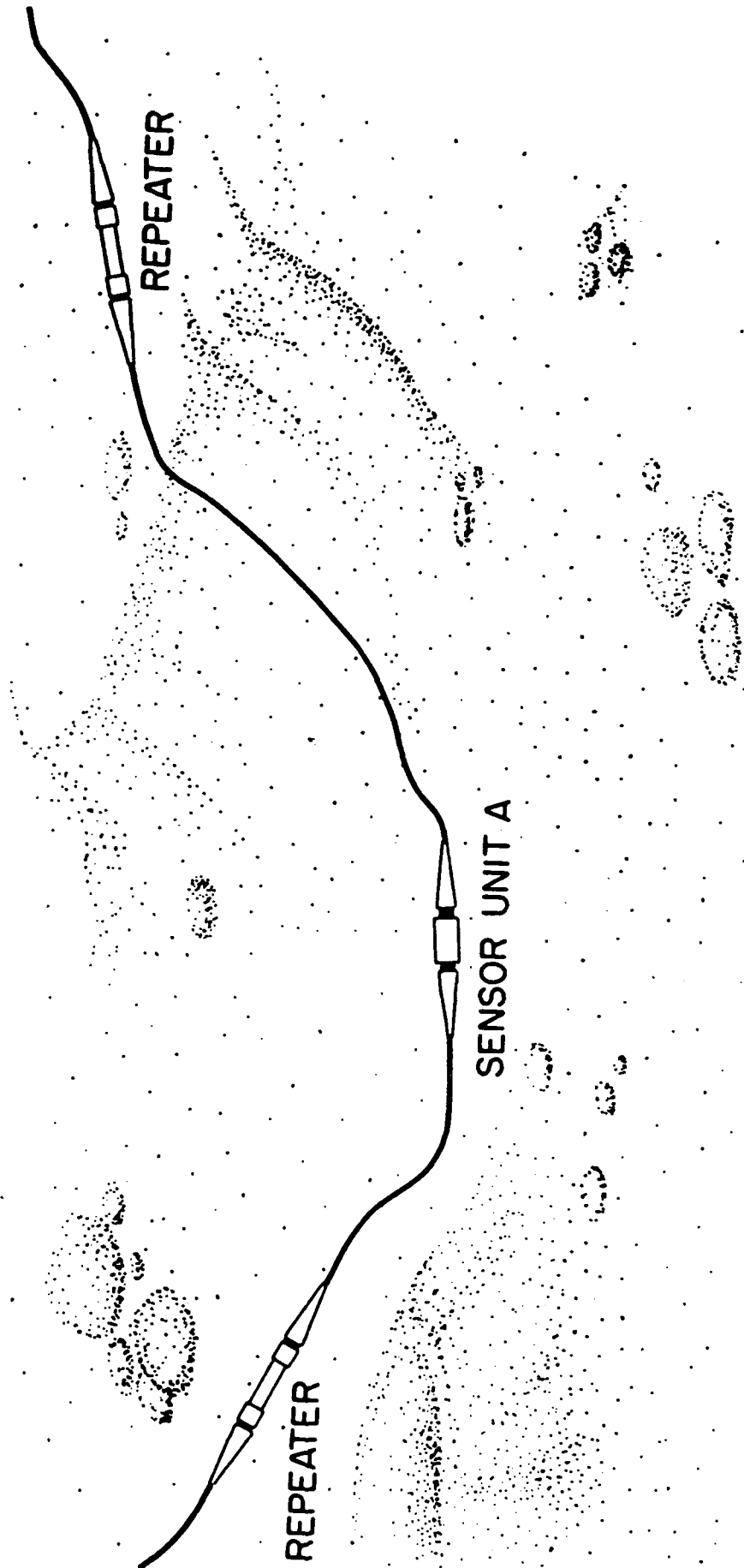


Fig. 3a

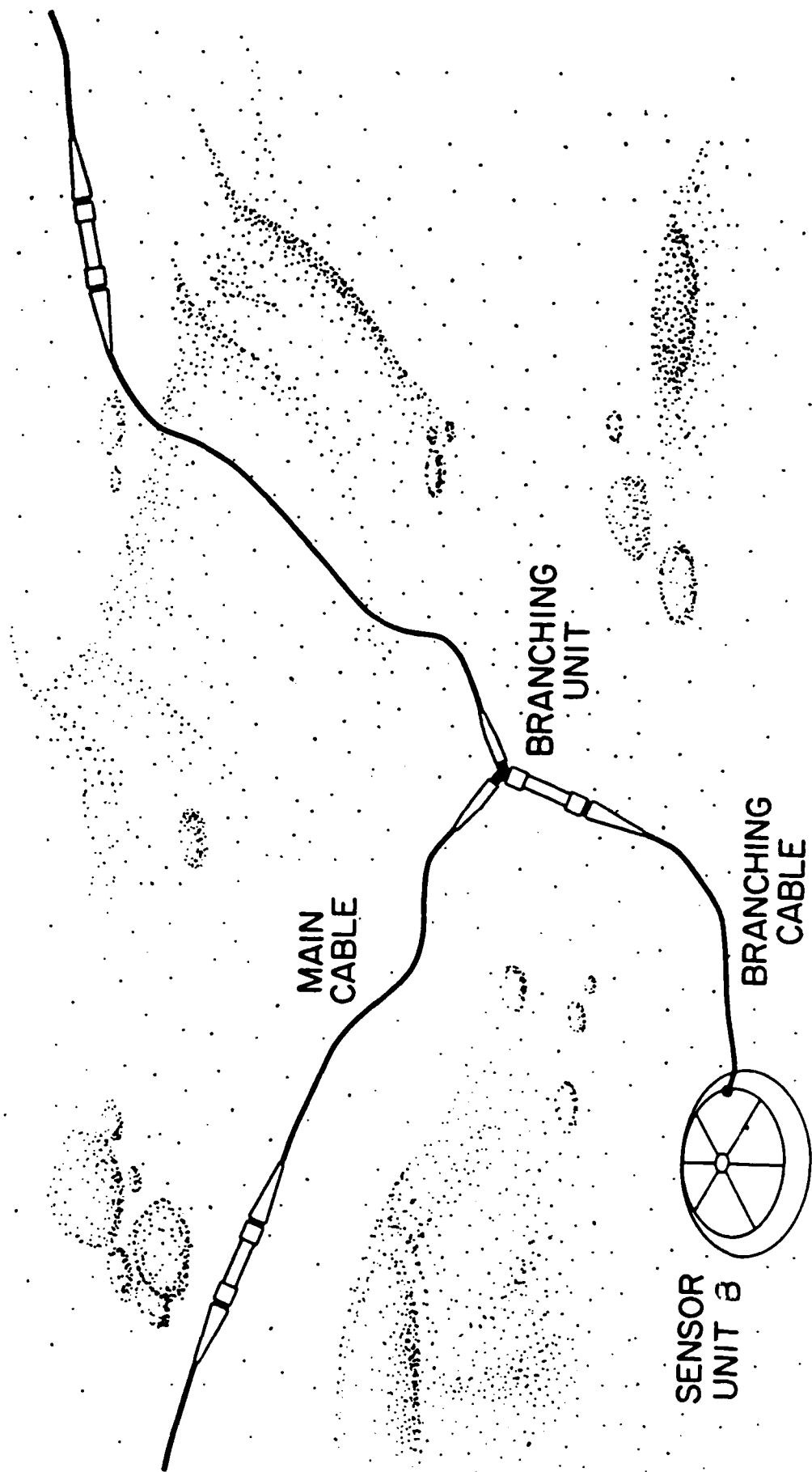


Fig. 3 b

